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AVIATION FUEL LUBRICITY EVALUATION

July 1988

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AVIATION FUEL LUBRICITY EVALUATION
(CRC Report No. 560)

Sincerely,

Beth Evans
Editor

BE:jer

Enclosures

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AVIATION FUEL LUBRICITY EVALUATION

(CRC PROJECT No. CA-45-58)

DAAK-70-86-C-0011

Prepared by the

Ball-On-Cylinder Lubricity Evaluator Operators Task Force

of the

CRC-Aviation Group on Aviation Fuel Lubricity

July 1988

CRC-Aviation Fuel, Lubricant, and Equipment Research Committee

of the

Coordinating Research Council, Inc.

ABSTRACT

A great amount of effort has been expended since the early 1960's for research and development on low-lubricity fuels, lubricity-enhancing additives, and test method development. The effort was initially directed at improving the lubricity characteristics of military JP-7 fuels, and then continued into the commercial engine area.

The Ball-on-Cylinder Lubricity Evaluator (BOCLE) has emerged as the test apparatus capable of providing a quantitative value for fuel lubricity. The precision of the test method was obtained for the home-built and for the commercial BOCLE units.

The effect of several test parameter changes in the procedure are detailed to give an indication of the potential variations produced in the test data.

TABLE OF CONTENTS

TABLES

TABLE OF CONTENTS - (Continued)

Page

TABLES - Continued

FIGURES

TABLE OF CONTENTS - (Continued)

FIGURES - (Continued)

APPENDICES

TABLE OF CONTENTS - (Continued)

APPENDICES - (Continued)

I. INTRODUCTION

1.1 SCOPE

The Ball-on-Cylinder Lubricity Evaluator (BOCLE) Task Force was established by the CRC Aviation Fuel Lubricity Group with the specific objectives to: (1) resolve and define details of the apparatus; (2) establish an operating procedure; and (3) plan and carry out a round-robin cooperative program. Membership of the Task Force and the laboratories that participated in the test programs appears in Appendix A.

1.2 FIELD EXPERIENCE

Fuel system components have experienced problems with the "slipperiness" or lubricity of the fuel back to the early 1960's.[1] As a consequence of the level of refinement necessary for the PWA 523 fuel (now designated MIL-T-38219 grade JP-7) to obtain its high-temperature stability, many of the polar compounds contributing to lubricity had been removed, resulting in abnormal hydraulic fuel pump wear. A lubricity-enhancing compound was developed (PWA 536) to eliminate the wear problem.

Beginning in the mid-1960's, additional fuel system components began to experience extreme reductions in life with other fuels. Interest was again directed toward fuel lubricity as the quantity of hydrogenated fuel in the marketplace became more pronounced.[2-8] In 1965, the Air Force demonstrated that the fuel was responsible for a series of unusual sticking problems of a fuel control. The fuel had been processed through clay filtration effectively removing the lubricity agents, and no corrosion inhibitor was added prior to use.

In 1966, the Lucas HP piston fuel pumps in the Avon-type engine experienced severe bore wear, ball-joint wear, and piston failure operating on Jet A-1 and Jet B fuels. The failure mechanism was described as: 1) high friction between the bore surface and piston; 2) the high surface temperature produced on the bore resulted in wear and ovality; and 3) the high temperature produced on the piston reduced the fatigue resistance on the surface and the bending load caused circumferential cracking and subsequent fracture.

The Pesco gear fuel pump in the JT-4 engine and the Chandler Evans gear fuel pump in the JT-3D engine also experienced problems at about the same time.

The JT-9D TRW fuel pumps encountered problems in 1971 when: 1) cavitation erosion occurred on the main stage gear teeth; 2) the gear teeth wore and fatigue failure started with metal-to-metal contact in the tooth contact area; (the first step was scuffing wear on the flank changing the tooth profile, producing interference causing fatigue and flaking of the contact surface. The subsequent hammering induced on the gears caused failure of the teeth by fatigue. The fatigue failure started at the erosion pit at the tooth root.); and 3) bearing cavitation from the pulsing of the gear shaft in the bearing.

The addition of corrosion inhibitors or a lubricity additive to the fuels has sucessfully alleviated the aforementioned problems.

1.3 FUEL LUBRICITY TESTING BACKGROUND

High-pressure piston-type fuel pumps were one of the first parts of the engine fuel system to exhibit problems related to fuel properties. One early problem manifested itself as corrosion of silver-plated slipper pads and was related to carryover of residual chlorides in fuel. One device used to investigate fuels associated with this problem was the Pin-on-Cylinder machine which employed a silver-plated bronze pin on a steel cylinder simulating the pump hardware. This device proved to be an excellent tool to investigate fuel lubricity in general. The pin was changed to either bronze or steel; wear rate of the pin proved to be a measure of the lubricating properties of fuel, with high rates reflecting the highly refined fuels that lacked natural lubricity agents.

Fuel controls were another part of the engine fuel system susceptible to fuel properties. Lack of lubricity agents caused fuel control sliding servo valves to stick. In the US, the Ball-on-Cylinder device pioneered by Furey was adopted as a lubricity tester to investigate fuels associated with the Air Force fuel control sticking problems of 1965. While this technique of rubbing one surface against another was similar in principle to the Pin-on-Cylinder test used in the UK, it proved to be much more sensitive for detecting the small amounts of corrosion inhibitor which proved to be excellent lubricity agents. A cross-check program comparing the two testers confirmed the advantages of the BOCLE approach and resulted in its general adoption.

Two other fuel lubricity testers were developed in this early period when problems related to fuel control sticking and pump wear first appeared. In the US, a fuel control simulator developed by Bendix was used to measure how long a fuel-lubricated sliding valve would operate before sticking developed. In the UK, a Dwell Tester developed by Lucas was created to measure the time for excessive friction to develop between a pin sliding on a disc containing a fuel film. The Dwell Tester was investigated by the CRC Aviation Fuel Lubricity Group in a joint US/UK program. In its original configuration, the Dwell Tester proved to be insensitive to known lubricity agents and was also superseded by the BOCLE-type test.

Lubricity is a fuel property that describes the ability of a film formed between rubbing metal surfaces under boundary lubrication conditions to reduce friction and wear. In the absence of a film, high friction and wear develop if localized corrosion occurs on the metal asperities. Hence, corrosion inhibitors which are excellent film formers are generally good lubricity agents. The role of corrosion in friction and wear has been confirmed by eliminating air and water from the system. A refined fluid exhibiting high BOCLE wear will behave like a lubricant when air is replaced by inert gas and the fuel is dehydrated.

1.4 FUEL COMPOSITION EFFECTS ON BOCLE RESULTS

Lubricity is one of the few fuel properties that may be degraded by certain refining processes. A great amount of effort has been expended in research and development on low-lubricity fuels and test method development since the early 1960's. The Ball-on-Cylinder Lubricity Evaluator has emerged as the test tool to provide a quantitative value to fuel lubricity. A measurement of the average wear-scar diameter on the ball is an indicator of fuel lubricity, with low values representing fuels of good lubricity. Early testing with the BOCLE demonstrated that the apparatus is capable of distinguishing between good and poor lubricity fuels, and can also detect the effect of additives on the fuels.

The change in quantitative test values using the original BOCLE design was evaluated with various different fuel compositions and test parameters.

The effects of changes in fuel composition on lubricity were evaluated using a series of JP-5 fuels blended with aromatic, olefin, and napthalene compounds. The test results presented in Table 1 show that these compounds lower the wear, but not by a sufficiently large size to be an effective lubricity-improver method. The effect of blending different batches of fuels is presented in Figure 1. The fuels include JP-5, clay-filtered JP-5, and 140 solvent. Blending small amounts of JP-5 with either clay-filtered JP-5 or 140 solvent results in a large decrease in wear, while blending clay-filtered JP-5 with 140 solvent results in a rougly linear graph of concentration versus wear-scar diameter (WSD) over the concentration range. The effect of dissolved oxygen on lubricity was determined with the same three test fluids as presented in Table 2. The removal of oxygen in the fuel appreciably lowered the wear of the clay-filtered JP-5 and the 140 solvent, but only a slight amount for the JP-5 fuel.

The effect of large load changes on lubricity for the above three fluids is presented in Table 3 where the wear from the JP-5 fuel exhibits steady increase, and the clay-filtered JP-5 and 140 solvent exhibits a maximum at low load followed by a rapid decrease followed by a slow increase at highest loads of 1400 grams. The effect of large changes in humidity on lubricity is presented in Figure 2 where these same three fluids illustrate different reactions to the humidity changes. The wear increased slowly with increasing humidity until the 40 percent relative humidity was reached. Further increases in humidity had no effect on wear, except for the clay-filtered JP-5 which continued to increase over the entire range of humidities. The performance of two different fuels in air atmosphere is illustrated in Figure 3 where RAF-176-64 and PW523 fuels are compared in dry and wet air. The wear for the RAF-176-64 fuel is greater in wet air, whereas the wear for the PW523 fuel is identical for both the dry and wet air. The argon exposure for both fuels produces the lowest wear, with both fuels relatively at the same wear level.

II. EARLY TEST METHOD DEVELOPMENT

2.1 APPARATUS DESIGN

2.1.1 Exxon/Woodward Ball-on-Cylinder Lubricity Evaluator

The Ball-on-Cylinder Lubricity Evaluator (BOCLE) is modelled after the Furey tester[10] which was developed to study metallic contact and friction between sliding lubricated surfaces. The Exxon Research and Engineering Company made design improvements during the performance on an Air Force contract[2] and, during this CRC program, additional improvements have been made by the Woodward Governor Company (Figure 4).

The BOCLE schematic shown in Figure 5 consists of a non-rotating 12.7 mm (1/2 inch) diameter test ball (A) held in a vertically-mounted chuck (B) and forced against the highest point on the outer surface of a 44.5 mm (1-3/4 inch) test cylinder (C). The ball and cylinder are positioned inside a rectangular reservoir (D) which contains 45-50 mL of test fluid, a sufficient quantity to cover the bottom portion of the cylinder. The cylinder is axially mounted on a horizontal shaft (E) that passes through the sides of the reservoir's upper detachable housing and is connected to a variable speed motor. The entire apparatus is mounted on a base (F).

Channeling in the base of the reservoir acts as a heat exchanger through which temperature-controlled water is flowed to permit test fluid temperature control. Holes drilled in the side of the reservoir (G) allow a purge gas to be bubbled through the fluid and to flow into the test chamber to control the atmospheric conditions and gas and water content of the test fluid.

A specified load is applied to the cylinder by hanging a weight on the hook (H) at the end of a balance beam (J). The beam is designed so that the ball is located exactly midway between the pivot point (K) and the mass hook (H). The vertical load on the ball is thus equal to twice the load applied at the mass hook.

The fluid is sampled and transported in borosilicate glass bottles, preferably amber-colored or covered with an opaque material to avoid possible reactions with sunlight.

The test apparatus exposed to the test fluid is cleaned in various solvents with ultrasonic cleaning becoming the most popular method.

The test balls are AISI standard steel No. E-52100 with a Grade 25 EP finish and a Brinell hardness of 682 to 712 (64-66 Rockwell C). The test cylinder is AMS 6444 consumable electrode vacuum melted premium aircraft-quality steel with a 4-9 AA micron-inch ground surface finish and a Brinell hardness of 226 to 237 (20-22 Rockwell C). The cylinders and balls are inspected under a microscope to eliminate specimens containing pits, corrosion, or surface abnormalities.

The rotational speed of the cylinder is set at 240 ± 2 rpm, and monitored with a tachometer. The fluid temperature is controlled at 25° ± 1°C by flowing constant temperature water through the reservoir base.

The supply air purity used for purge gas is maintained at less than 0.1 ppm hydrocarbons and 50 ppm water. The purge gas is adjusted to a 10 ± 0.2 percent relative humidity with the atmosphere control unit shown in Figure 6. The system consists of the dry air flow from the supply cylinder (A) which is split into two portions, each with its flow valve (B). The air flow in one portion goes directly to the flowmeter (C1). The air from the second portion flows through the humidifier (D) to the flowmeter (C2). The two portions of air are again united and progress through the wet test meter or rotameter (E) for final flow measurement of 3.776 L/min (8 SCFM). The air is monitored by the hygrometer (F) to assure relative humidity of 10 ± 0.2 percent. The purge air temperature must be controlled at 25° ± 1°C to assure an accurate hygrometer reading. The relative humidity is adjusted by calculating the flow rate required for the humidifier or 100 percent relative humidity portion, and then adjusting dry air portion to obtain the required total flow. The adjusted air flow is divided with 15-25 percent of the total flow bubbled through the test fluid and the remainder through the reservoir for fifteen minutes prior to the start of the test to assure that the fluid is at the proper condition.

With all the air directed over the test liquid, and application of a 1000-gram load on the cylinder, the test is initiated and continues for 30 ± 0.1 minutes.

The wear-scar diameter on the ball in millimeters is observed and measured at 100X for the major and minor axis using the best fit ellipse method. The result reported as the wear-scar diameter is the average of this pair of measurements.

Each new cylinder and equipment modification is calibrated with a reference standard in which sufficient experience or a historical data bank provides a known wear-scar diameter value.

2.1.2 InterAv Ball-on-Cylinder Lubricity Evaluator

Prior to Round-Robin II, a commercial unit was designed and produced by InterAv Inc., San Antonio, Texas (Figure 7) at the request of the US Air Force.

The basic design of the BOCLE is similar in principle to the Exxon/Woodward unit and incorporates stability and protection against lateral movement of the balance beam loading arm and permits precision control of relative humidity, temperature, and spacing of wear tracks.

All controls of the unit are contained in a compact cabinet. The tester is semi-automatic in that the purge cycle and test cycle are automatically timed without operator attendance. The tester has a built-in micrometer for cylinder track positioning. The stainless-steel test reservoir and aluminum cover permit aeration and purging cycles to take place in the reservoir.

The integral cooling/heating compartment of the test reservoir permits temperature control and lends itself well to elevated temperature work with the addition of an appropriate external recirculating bath.

Instrumentation is in the form of electronic digital display. Instrumentation includes a built-in hygrometer and indicator for 0-100 percent relative humidity, a digital RPM/torque indicator, conditioning air temperature indicator, and an electronic test timer. The test timer actuates a solenoid valve which lifts the ball off the cylinder at the conclusion of the test period. An actuator switch automatically lowers and raises the balance arm by means of a pneumatic actuator.

Self-contained are air dryer and humidifier units, and flow meters for dry air, wet air, conditioned air, and purge air. An alarm horn actuates upon cycle completion.

2.2 BOCLE ROUND-ROBIN I

2.2.1 TEST METHOD

The first draft of the test method was prepared with special consideration of the following details.

Balls

The source and specification for test balls were 1/2-inch diameter, AISI 52100 steel, R_c 62-64, Grade 25 EP manufactured by SKF for the Shell four ball tester (ASTM D-2596) and sold by SKF and Roxana Machine Works Co., South Roxana, Illinois.

Cylinders

The cylinder specifications were AISI 52100 steel quenched and tempered to R_c 20-22, 1.750 inch (4.4450 cm) diameter, 0.75 inch (2 cm) width, centerless ground outer surface to 4-9 micro-inch CLA surface finish. Each laboratory would supply its own cylinders with only the final grrinding performed by a single source, Advance Centerless Grinding Co., Lyndhurst, New Jersey.

Operating Conditions

A detailed list of operating conditions is found in Table 4. Several laboratories reported that their operating temperatures sometimes fell outside the desired 77 ± 3°F range; however, no significant changes in test results were observed because of the deviations. The test fluid temperature can be controlled to within ±0.5°F by circulating constant temperature water through the reservoir base.

The importance of maintaining a constant relative humidity in the purge air was stressed. All air entering the system was limited to 0.1 ppm hydrocarbons and 50 ppm water. The portion of dry air that was split off and saturated had to pass through at least two water-filled spargers in series (this gave approximately 95 percent saturation, one sparger gave approximately 85 percent saturation) before being remixed with dry air to give the final 10 percent relative humidity blend.

Cleaning Procedure

Recommendations were that the thermocouple tube on the bottom of the reservoir be moved to facilitate cleaning, and that the reservoir be modified to allow disassembly for cleaning between runs, with all cracks and crevices on the inside of the reservoir filled in or smoothed out to prevent fluid entrapment.

Wear Scar Measurement

The location of the outer edge of the wear scar for measurement when the edges of the scar are irregular is described on a photograph of typical wear scars (Figure Q-6, Q-7, Q-8). For this program, the "best-fit ellipse" method was used, which involved visually estimating where the outer edge of a smooth elliptical scar would fall if edge irregularities were not present.

Reference Fluids

Reference fluids were necessary with well-defined compositions (i.e., pure materials or mixtures of pure materials). Materials such as jet fuels or Stoddard Solvent (MIL-C-7024B) were not suitable reference fluids because of batch-to-batch variations. If a mixture of pure materials was used as a reference fluid, all of the ingredients should have had similar boiling points to minimize changes in composition due to selective evaporation during the test. In addition, because of the wide range of fluid lubricities expected to be encountered, it was deemed likely that at least two reference fluids would be needed; one with good lubricity, and one with poor lubricity.

2.2.2 Round Robin I Program

In 1977, the first Round-Robin cooperative program was initiated with nine laboratories ready to participate (Table 5).

Thirteen fluids were included in the program (Table 6), with eight considered to have poor lubricity and five considered to have high volatility. Each fluid was tested in duplicate under the standard operating conditions except for the isooctane and 70:30

isooctane/toluene mixture which was run at a 100-gram load, because scuffing occurs at higher loads. All details supplied for the program are included in Appendix B.

2.2.3 Round-Robin I Results

The results of the BOCLE tests are given in Table 7, the measured properties of the cylinders in Table 8, and the calculated averages and standard deviations for the individual test fluids along with the overall repeatability and reproducibility in Table 9.

A number of data points in Table 7 are marked with an (S) to indicate that scuffing occurred during the run. These Data were not included in subsequent calculations, because scuffing wear-scar diameters (WSD) have not been correlated with non-scuffing wear-scar diameters. The procedures given in ASTM RR:D-2-1007, "Manual on Determining Precision Data for ASTM Methods on Petroleum Products and Lubricants," were used to derive replacement values for the rejected data.

Several data points in Table 7 are marked with an (R) to indicate that a run was repeated. Repeat runs were not included in the calculations in Table 9, because the test program specified only two data points per sample.

During the analysis, procedures were employed to determine, if any individual data points, entire samples, or laboratories were outliers (results far enough in magnitude from other results so as to be considered not a part of the set). The results showed that none of the samples or laboratories were outliers, but that several individual data points were outliers; however, removing the outliers from the data set had only a small effect on overall results.

The repeatability of the test, determined from this Round-Robin I or the difference between successful results obtained by the same operator with the same apparatus under constant operating conditions or identical test material would, in the long run, in the normal and correct operation of the test method exceed 0.196 mm in only one case in twenty.

The reproductibility of the test, or the difference between two single and independent results obtained by different operators working in different laboratories or identical test material would, in the long run, exceed 0.371 mm only in one case in twenty.

2.2.4 Test Modification

The magnitude of the repeatability and reproducibility in the Round-Robin I program was a surprise, and greater than the precision (reproducibility) goal of 0.1 mm. An investigation of the variables that would account for the wide variations in wear was carried out as follows:

Cleaning Procedures

The results of a questionnaire on the BOCLE cleaning procedures indicated that there were differences between laboratories, and that not all laboratories followed the details of the procedure. All laboratories should use the same cleaning procedures to minimize sources of variation.

Effect of Final Rinse

The addition of a final rinse with test fluid was studied (Table 10), with three fuels covering a wide range of wear-scar diameters: JP-5, clay-filtered JP-5, and 140 solvent. Each fuel was run on the BOCLE twice a day for four consecutive days. On two of the days, the normal between-runs cleaning procedure of rinsing and wiping the reservoir and cylinder with isooctane was used. On the other two days, the isooctane rise was followed by a test fluid rinse. This consisted of adding 20 mL of test fluid to the reservoir, rotating the cylinder at 100 rpm for 10 minutes, and then removing the fluid by aspiration. The test fluid rinse was followed immediately by the normal test run. Test results indicate that there is no significant difference between final rinses in either WSD or standard deviation.

Effect of Temperature

A sample of JP-5 fuel was evaluated over a range of temperatures to determine the effect of temperature of WSD. The samples were run under standard conditions except for temperature. Results are shown in Figure 8. The temperatures are the average of the initial and final temperature of the fuel in the reservoir. The reservoir temperature usually increased between 1° and 3°F during a run. The data indicates that temperature had a significant effect on WSD. It appears that a change in average operating temperature of 6°F would result in a change in WSD of about 0.06 mm. These results indicate that a smaller temperature range would improve precision.

2.3 MINI-ROUND-ROBIN I

2.3.1 Test Method

The Mini-Round-Robin I was designed to determine the effect of changes in materials and operating procedures adopted by the Task Force. These changes included the use of cylinders heat treated to a hardness of 28 Rockwell C, the etching of test balls prior to testing in order to position the wear scar in the non-polar/equatorial location, and strict adherence to cleaning and operating procedures.

The magnetic orientation of the test ball was an important part in the study of lubricant behavior.[11]. An investigation at several laboratories showed that the control of the ball orientation does reduce the scatter of the wear-scar size.

2.3.2 Mini-Round-Robin I Program

The Mini-Round-Robin I program was limited to four laboratories to keep the number of tests to the minimum required if the changes adopted would improve the precision of the test. The laboratories were Exxon, Pratt & Whitney, Sundstrand, and NAPC.

There were four fuels in the program: JP-5, clay-filtered JP-5, clay-filtered JP-4, and Harpoon Fuel.

Complete details of the program are given in Appendix C.

2.3.3 Mini-Round-Robin I Results

Test results from the BOCLE Mini-Round-Robin I are presented in Table 11, along with the overall and individual laboratory averages and standard deviations for each test fuel.

The basic measurements, or raw data, were the major wear-scar diameter and the minor wear-scar diameter of each ball tested. From these basic measurements wear-scar diameters (WSD) and wear-scar volumes (WSV) were calculated. Appendix D gives the data and their dimensions organized by fuels and laboratories. Analysis of both of the WSD and WSV measurements were carried out.

The data were organized into two groups. One group used all of the data, titled Four Laboratories in the tables. The other group, titled Three Laboratories, does not include the test results from a laboratory that ran the tests at a higher humidity, 30 percent. Because of the relatively small amount of data for an interlaboratory test to estimate precision parameters, the data were analyzed using these groups. Also, within each group, for both the WSD and WSV values, no data were discarded as outliers. This makes the results of the analysis somewhat conservative.

The statements that follow are given in terms of wear-scar diameters (WSD) measurements only. The tables show that comparable conclusions can be made for the volume results.

The Harpoon fuel, for all laboratories, has the highest WSD, but in general has the lowest variability. The variability of the other three fuels does increase with increasing diameter.

Table 12 gives the repeatability and reproducibility intervals for this data set. The WSD repeatability estimates are about the same for the Three Lab or Four Lab group. This is because, although the eliminated laboratory data values were higher than the others, the variability of those measurements was about the least of all. The repeatability intervals do vary with mean WSD level. The noted exception is the Harpoon fuel in both groups. These precision parameter estimates state that if the difference between the sample average of three measurements made on one ball and the sample average of three measurements made on another ball is found, then the absolute value of this difference will be less than the table values 95 percent of the time. The repeatability precision estimates the variabilities between fuel samples in the same laboratory.

The reproducibility intervals in Table 12 are larger for the Four Lab group than the Three Lab group. These precision estimates contain all the other variability effects on the data. The reproducibility estimates state that if one measurement is made for a fuel sample in one laboratory and one measurement is made for another sample of the same fuel in another laboratory, then the absolute value of the difference of the measurements will be as given in Table 12. The exception is for the Harpoon fuel in the Three Lab group.

Appendix E separates the contribution of each source of variability in the data due to main effects, laboratories, samples, and measurements. The values given there are in terms of variances rather than standard deviations. Again, it is seen that the total variability due to all causes, the total variance row for each fuel, increases with increasing WSD except for the Harpoon fuel. The percentage contribution of each source of variability to the total variance is given also. Note in the Four Lab group that the between-laboratories effect predominates over the between-fuel-samples-within-laboratories effect. In the Three Lab group, however, the between-fuel-samples effect predominates much more. This means a good portion of the between-laboratories effect when using all the data is due to the eliminated laboratory data. Since the Three Lab data are more homogeneous set, the components of variance for each fuel show that the laboratories are quite similar in technique. Also, the variability is now due to the particular fuel samples.

For the Three Lab group, Appendix F gives sample averages and ranges for the three measurements made on each ball by each laboratory. It also gives the mean and standard deviation for the total number of measurements made by each laboratory on each fuel, and the mean and standard deviation for all the measurements made on each fuel. The Pratt-Whitney CFJP5 row in the table shows their averages to be lower than the other two laboratories, but the standard deviations are the same. This difference contributes to the reproducibility intervals for the CFJP5 in Table 12 and to the between-laboratories effect for the Three Lab group in Appendix E. The CFJP5 between-laboratories effect is the largest in that group.

Appendix G for the Four Lab group gives the same information as Appendix F. The low standard deviation of the eliminated laboratory measurements can be seen. Also, the higher mean level stands out in the deviations column which shows the difference between the fuel average to which all the laboratories contributed and the particular laboratory averages. In most cases, the other three laboratories have negative deviations. This effect contributes to the between-laboratories variability in the Four Lab group. In Appendix E, note the difference in the between-laboratories components of variance in each of the groups. The Four Lab group variances are substantially higher.

Some of the laboratories experienced different operational problems, such as not holding temperature, need to regrind a cylinder, trouble etching balls, and using different cleaning procedures. Regardless of these effects, the Three Lab data set shows the BOCLE test of lubricity precision to vary from 0.04 mm to 0.12 mm in WSD repeatability (a 95 percent confidence interval), and to vary from 0.05 mm to 0.21 mm WSD for between-laboratories reproducibility (a 95 percent confidence interval).

2.3.4 Operation Improvements

The results of the Mini-Round-Robin I demonstrated an improvement in the standard deviation up to 84 percent compared to Round-Robin I. This significant improvement indicated that several of the test variables in the first program were under better control in the mini-program; however, the precision between laboratories was still not satisfactory. The following changes to the test method were expected to improve the precision.

Cylinder Hardness

The hardness selection of 20-22 R_c was attained more readily and with greater reproducibility than other hardness levels.

Magnetic Orientation

The etching and orientation of the test balls was a technique that does improve precision, according to several laboratories. There were other items necessary to improve the precision, however, before the effect of the magnetic orientation could be definitely confirmed as an advantage.

Purge Air Relative Humidity

A control on the purge air relative humidity was one of the most important factors to improve precision. An accurate hygrometer was necessary to determine the relative humidity of the air that flows through the fuel and test reservoir.

The data proved that relative humidity of the purge air at levels other than 10 percent does not improve test precision. Thus, the considerable bank of important data generated thus far on engine performance would remain valuable with continued use of the 10 pecent relative humidity.

Test Arm and Cylinder Shaft Lateral Motion

The possibility existed that lateral motion of the test arm relative to the cylinder shaft would produce a loss of precision. This warranted adoption of the Woodward Governor Company design change to eliminate the lateral motion.

2.4 MINI-ROUND-ROBIN II

2.4.1 Test Cylinder Problems

The quality of test cylinders with respect to microstructure, surface finish, and uniformity was known to be poor. The testing schedule was designed to answer the question of uniformity of pairs of cylinders as well as the efficiency of cleaning.

A metallurgical analysis was made on a pair of cylinders with the same hardness and surface finish but different wear scar dimensions with the same fluid. The cylinders were sectioned, etched in nital, and subjected to optical microscopy by Exxon Research and Engineering Company. The observation was that the "poor" cylinder showed a much greater concentration of carbides dispersed in the bulk phase, which would account for higher wear on the ball despite the unaffected cylinder hardness and surface finish. Since the carbide dispersion resulted from heat treating, grinding or additional heat treating would not correct the problem.

A microstructure examination of two types of cylinders, an annealed AMS 6440 of R_c 22 which gave good results, and a heat-treated cylinder of R_c 20 of poor quality, was conducted by Sundstrand. In measuring microhardness of the surface layer, the latter cylinder appeared to be banded and more variable than the annealed cylinder. The poor cylinder had more sulfide inclusions and showed "blakey" carbides rather than elongated grain boundaries. Examination of surface finish by Tallysurf of three different cylinders that meet current specifications showed two to have a uniform number of asperities, while a third varied considerably. The surface finish was concluded to be as important as microstructure in explaining different results.

A short program investigated the effect of the test cylinder alloys and surface finish condition on test results.

2.4.2 BOCLE Mini-Round-Robin II Program

The Mini-Round-Robin II program was performed by six laboratories that tested two alloys each with two methods of finishing the surface on two fuels. The surface condition of the cylinders is given in Table 13 and the complete test details are given in Appendix H.

2.4.3 BOCLE Mini-Round-Robin II Test Results

The test data from the Mini-Round-Robin II program is included in Appendix I. Several results were excluded from subsequent analysis because the laboratory reported severe chattering or was obliged to abort the test before completion.

Mean WSD results of the four tests which each laboratory conducted with each test cylinder pair appear in Table 14. Reference fuel (shale JP-4) produced wear scars about twice as large as test fuel (spec JP-4). Laboratories differed considerably in the average wear scars measured for each cylinder. There appeared to be no difference in average values for AMS 6440 versus 6444, but the lapped surface always showed lower values than the ground surface. When the precision of results was calculated, however, none of the differences shown in Table 14 proved to be significant.

Variances of repeat values for each combination and laboratory were calculated, with results shown in Appendix J and expressed as repeatability and reproducibility using the normal 95 percent confidence limits. For reference fuel, repeatabilities of WSD varied from 0.124 to 0.288, but differences were not significant. For test fuel, repeatabilities of WSD were significantly lower than for reference fuel and varied from 0.053 to 0.097, but again differences among cylinders were not significant.

Reproducibilities were generally higher than repeatabilities, but not twice as high as one would expect. The primary source of error, therefore, was within each laboratory and the ability to repeat results. The average wear scar results and standard deviations of repeatability for each laboratory are listed in Appendix K. For each cylinder quality, there was a wide range of standard errors. Each laboratory tended to show high standard errors on one or more cylinders qualities, suggesting that the test procedure rather than the cylinder itself was the prime source of error.

The net conclusion to be drawn from this analysis was that it is impossible to select a preferred cylinder alloy or finish on the basis of the test precision achieved in this program.

2.5 BOCLE ROUND-ROBIN II

2.5.1 Commercial BOCLE

Aircraft engine fuel pumps were found with excessively high wear rates when operating on shale JP-4 fuel. The shale JP-4 fuel was found to have lubricity values by the BOCLE higher than was customary for normally available petroleum JP-4 fuel. InterAv Inc., San Antonio, Texas, was contracted to manufacture BOCLE units with more ruggedness than the original design and to provide more automation with a good humidity control system, with precise flowmeters and a hygrometer in the air supply line. Ten of these units (Figure Q-1) were available for the Round-Robin II program.

2.5.2 BOCLE Round-Robin II Program

The Round-Robin II program included participation of laboratories with eight Exxon/Woodward BOCLE units and ten InterAv BOCLE units as shown in Table 15.

There were eight fuels distributed, with four rated high-volatility and four low-volatility to permit an analysis of the evaporation factor, and two each of high and low lubricity and four of medium lubricity to provide a range of typical ball-wear readings as shown in Table 16.

The BOCLE tests follow Draft 5 of the test method as included in Appendix Q. The test details are given in Appendix L.

2.5.3. BOCLE Round-Robin II Test Results

The individual Round-Robin II test results from the laboratories with tests on the Exxon/Woodward BOCLE units are given in Appendix M with a summary in Table 17. The supplementary data covering specific aspects of the procedure for each of the laboratories is included in Appendix N.

The individual Round-Robin II test results from the laboratories with tests on the InterAv units are given in Appendix O with a summary in Table 18. The supplementary data covering specific aspects of the procedure for each of the laboratories is included in Appendix P.

Chevron Research Company performed the statistical analyses of the data and reported the following:

2.5.3.1 Ground Rules For Statisical Analysis

The precision study consisted of eight different fuels, tested in duplicate, at 10 percent relative humidity. The eight fuels included three levels of lubricity (determined by preliminary BOCLE tests) and two levels of volatility.

A factorial test, separate from the precision study, was designed to determine the effect of cylinder-to-cylinder variation and humidity of BOCLE results. The factorial test used four of the eight fuels from the precision study and tested at 10 percent and 50 percent relative humidity. The four fuels included two levels of lubricity and two levels of volatility.

2.5.3.2 Wear-Scar Description

Three functions of the major and minor wear-scar diameters (d_{mjr} and d_{mnr}) were considered for describing the extent of wear on the ball. Two estimated an average wear scar diameter:

$$d_{ws} = (d_{mjr} + d_{mnr})/2 = \text{Wear-Scar Diameter} \qquad (1)$$

$$d_{wsa} = \sqrt{(d_{mjr})\ (d_{mnr})} \qquad (2)$$

The third function estimated the volume of metal removed from the ball, assuming a circular wear scar of diameter d_{ws}:

$$V_{ws} = \frac{\pi}{3}\left[2r^3_{ball} - \left(\left(d_{ws}/2\right)^2 + 2r^2_{ball}\right)\sqrt{r^2_{ball} - \left(d_{ws}/2\ ^2\right)}\right] \qquad (3)$$

where r_{ball} is the radius of the ball used in the test (6.35 mm).

A precision analysis of the round-robin data indicated none of these functions was suitable for statistical analysis, because their variances were not constant across their range of values. A relatively constant variance (homogenized variance) is a necessary condition in an analysis of variance, the technique used in analyzing the data. As shown in Figure 9, the standard deviation of the wear-scar diameter increases with increasing mean wear-scar diameter. (Only data for tests run at 10 percent humidity are shown in Figure 9 for convenient illustration.) Transforming the results of the ball-on-cylinder test to $(d_{ws})^{-5/4}$ homogenizes the variance as shown in Figure 10. Precision analysis of d_{wsa} and V_{ws} showed the transformations $(d_{wsa})^{-5/4}$ and $(V_{ws})^{-1/3}$ would homogenize their variances. Note that the transformations of all three functions have about the same dimensions of (1/Length). The physical meaning of this condition is not known, but it is consistent that all three functions converged to this form.

2.5.3.3 Result of the Statistical Analyses

2.5.3.3.1 ASTM Precision Study

Analysis for the precision study included data from sixteen of the eighteen BOCLE machines which were used in the round robin. Data from two of the machines were not included in the analysis because those tests were not run at the humidity specified in the test design. Table 15 summarizes the laboratories participating in the precision study. The statistical analysis included all data from the sixteen machines--six CRC and ten InterAv machines.

The precision of the BOCLE was determined based on an analysis of the data according to the guidelines of ASTM RR:D-2-1007:

$$\text{Repeatability} = 0.489\ (d_{ws})^{2.25} \qquad (4)$$

$$\text{Reproducibility} = 0.882\ (d_{ws})^{2.25} \qquad (5)$$

These functions are illustrated in Figure 11. The functions represent the 95 percent confidence interval for the difference between the results of two tests.

2.5.3.3.2 Variables Affecting the Magnitude of BOCLE Results (Factorial Test)

Statistical analysis of the factorial test included data from nine of the eighteen BOCLE machines which were used in the round robin. Only laboratories reporting results for the full factorial experiment were including in this analysis. This was done to avoid an unbalanced test design.

Analysis of the factorial experiment results shows that both test humidity and test fuel have a significant effect on the size of a wear scar generated during a BOCLE test (99 percent confidence level). The effect of test fuel on ball-on-cylinder results indicates this test can discriminate between fuels. This result also indicates that a good selection of test fuels was made for this program. The significant effect of humidity demonstrates that this variable must be controlled to ensure good test precision, because increasing humidity increases the severity of the test and results in larger wear scars. As discussed previously, humidity was controlled at 10 percent during the precision study.

Analysis of the factorial results also shows that test cylinder and test machine do not have a significant effect on the magnitude of the wear scar. Thus, as a group, the InterAv machines generated about the same size wear scars as did the CRC machines for a particular fuel. Also, cylinder-to-cylinder variability did not have an appreciable effect on the size of the wear scars generalted during the test.

2.5.3.3.3 Variables Affecting the Precision of the BOCLE Test

The analysis of the ball-on-cylinder round-robin data indicates that some test variables have a significant effect on test precision. The details are given in Table 19.

Test machine had a significant effect on BOCLE precision. The InterAv machine had significantly better precision than the CRC machine (99 percent confidence level) even though the average wear-scar diameter for a given fuel was approximately the same for both machines. The difference in precision may be due to less variability in the geometry of the InterAv machines since they were all manufactured by a single company.

Test humidity also had a significant effect on BOCLE precision, as well as on wear-scar size. Tests run at 10 pecent humidity had better precision than those run at 50 percent humidity (95 percent confidence level). Test fuel volatility had a significant effect on ball-on-cylinder precision. Fuels with low volatility gave more precise results than did high-volatility fuels (95 percent confidence level). This difference may be due to variability in the amount of fuel which evaporates during the ball-on-cylinder test, which affects the viscosity and composition of the test fluid during the experiment.

2.5.3.3.4 Wear-Scar Measurement

The variability in measurement of wear-scar dimensions does not contribute appreciably to the variability of the BOCLE test. Statistical analysis of the results of the wear-scar measurement round-robin shows good precision over a broad range of wear-scar diameters:

$$\text{Repeatability} = 0.054\ (d_{ws}) \qquad (6)$$

$$\text{Reproducibility} = 0.105\ (d_{ws}) \qquad (7)$$

Note that these values are considerably less than those shown in Equations 4 and 5. This is especially true for tests resulting in large wear scars, because the difference between the two pairs of equations becomes quite large. Thus, most of the variability of the BOCLE test occurs in the generation of the wear scars and not in their measurement.

The laboratories participating in the ball-on-cylinder round-robin reported both wear-scar diameters and the corresponding cylinder track width. This was done to determine if track width was a more precise measure of ball-on-cylinder wear. Laboratory-to-laboratory variability for track width measurement was large compared with wear-scar diameter, however, and it was not used to determine a BOCLE precision statement. One source of this variability is measurement error, since a procedure for measuring track width was not included in the round-robin instructions. Any subsequent round-robins should include instructions for measuring track width and should require multiple measurements of track width around the test cylinder if it is intended to use this variable in the analysis. This approach will systematically reduce random variability and improve measurement precision.

2.5.3.3.5 Geometric Criterion for Evaluating BOCLE Test Results

The ideal relationship between major and minor wear-scar diameters may be developed from the geometry of the BOCLE wear-scar, which is essentially the intersection of a cylinder and a ball. This is expressed mathematically as:

$$d_{mnr} = \frac{d_{mjr}\,(\sin\gamma)\ \ r_{ball}\,(\sin\theta)}{(\sin\phi)\left(r_{cyl} + \sqrt{r^2_{ball} - (d_{mjr}/2)^2}\right)} \tag{8}$$

Where:

r_{ball} = Radius of Ball = 6.35 mm

r_{cyl} = Radius of Cylinder = 22.22 mm

$$\phi = \mathrm{Tan}^{-1}\ d_{mjr}/2r_{cyl}$$

$$\gamma = \mathrm{Tan}^{-1}\ 2r_{cyl}/d_{mjr}$$

$$\theta = \mathrm{Cos}^{-1}\left(\frac{(d_{mjr}/2)^2 - 2r_{cyl}\sqrt{r^2_{ball} - (d_{mjr}/2)^2}}{2r_{ball}\,r_{cyl}}\right)$$

This theoretical relationship between major and minor diameters is concave upward, but is approximately linear (+/- 1%) in the range observed in the round-robin (d_{mjr} <3.0 mm). Thus, the relationship in Equation 8 can be simplified to a linear relationship:

$$d_{mjr} = 1.133 \ (d_{mnr}) \qquad (9)$$

As shown in Figure 13, the data from the round-robin agree with the relationship predicted by Equations 8 and 9 except for very large wear scars, for which the major wear-scar diameter is larger than would be expected from the minor diameter. Laboratories reported grinding or chattering during many of these tests, which may indicate the test results were invalid due to unusual dynamic behavior of the machine.

The relationship between major and minor diameters may be used as a criterion for reviewing ball-on-cylinder test results. Results falling outside the envelope of values shown in Figure 15 may be considered suspect and the wear scar remeasured or the test repeated. Note that the two lines defining the envelope in Figure 15 both have a slope of 1.133, which is consistent with Equation 8. As shown in Figure 15, one test result from the round-robin fell outside the acceptability envelope developed using this geometric criterion. This result was not rejected from the precision study, however, because the average of the major and minor wear-scar diameters (d_{ws}) was similar to other results, even though the ratio of major to minor diameters was quite different.

Additional analyses were conducted to compare the precision of the Exxon/Woodward design and InterAv units, and the relationship between track width and the major wear-scar diameter. The comparison of the two BOCLE units shown in Figure 12 indicated that the InterAv unit repeatability range was slightly less at the lower wear levels, and this difference decreased until they were essentially equal at 1 mm WSD. Above 1 mm, the opposite conditions apply; i.e., the Exxon/Woodward units gave less of a repeatability range. The same pattern applied for the reproducibility, but the crossover point between the two units was at the 0.78 mm WSD mark. Measurement of the track width of the cylinders given in Figure 14 shows remarkably good correlation with the wear-scar diameter of the test balls for some laboratories and very poor agreement with other laboratories. The possible explanation for the poor correlations is that the unfamiliarity of measuring a cylinder gap accounts for a greater than normal error.

2.5.3.3.6 Additional Comparison

A review of the Round-Robin II data led to a concern that the measurement of the wear-scar diameters of the test balls may contribute detrimentally to a greater extent than expected to the test procedure. A plan was designed to determine the extent that the precision is dependent upon the wear-scar diameter measurement. The Air Force selected eighteen test balls exhibiting the range/wear values and scar appearances normally obtained from the test. These test balls were sent to each of the thirteen participating laboratories in groups of six on a rotating basis. A compilation of the measurements is given in Table 20.

An analysis of the data indicates that there was no unusually large effect on the precision of the BOCLE test method produced by the measurement of the wear-scar diameters. There was good precision over the broad range of wear-scar diameters.

The comparison of the relationship of the major diameter to the minor diameter demonstrated that there may be merit in considering the rejection of test results which fall outside an established envelope of values as shown in Figure 15.

III. FINAL TEST METHOD DEVELOPMENT

3.1 BOCLE MINI-ROUND-ROBIN III

3.1.1 Test Method Improvements

The uniformity of the test cylinders continued to be a problem when subsequent lots from the supplier failed to produce reproducible test results. The surface finish of the cylinders was found to vary considerably from the required 4-9 microinches AA. The cylinders that conformed to the specification requirements for alloy, hardness, and surface finish were still found unable to duplicate previously obtained test results.

Data were introduced to indicate that Timken cups (per ASTM D 2782) adapted to the BOCLE configuration (BOCLE test rings) supplied by the Falex Corporation provided more consistent results than the test cylinders. A comparison, given in Figure 16, showed that the test ring varied from 70 percent to 110 percent higher wear-scar diameters in the normal fuel range dropping to 30 percent higher at the high wear-scar diameters. The test cylinders supplied by two manufacturers varied from each other by 12-18 percent WSD.

Additional testing indicated that the two manufacturers produced cylinders with WSD repeatabilities from 0.075 to 0.111 mm while the test ring was 0.014 mm. The data are given in Table 21. The excellant reproducibility between different lots of test rings, with a maximum range of 0.02 mm, is shown in Table 22 and illustrated in Figure 17. The measurement of the wear-scar diameter for the test ring was also improved over that of the test cylinder as shown in Figure 18.

Test runs were made with test rings of three different surface finishes. The results, given in Appendix S, show that the surface finish gratly influences the degree of ball wear in the same manner as previously observed with the test cylinders. The test rings with surface finishes in the 10, 25, and 45 RMS ranges produced wear-scar diameters of 0.45, 0.49, and 0.55 mm with a high-lubricity fluid and 0.73, 0.76, and 0.78 mm with a low-lubricity fluid, respectively.

The typical wear-scar diameter differences in test results for various fluids between the test cylinder and test ring was found to be 0.16 mm to 0.29 mm higher for the test ring. The data are given in Appendix R.

The specific source of the test balls was found difficult to ascertain since the normal suppliers obtained them from more than one manufacturer and then commonly mixed them. Because of the rigid control of the manufacturing process and handling, the balls from SKF Sweden and designated RB 12.7 were chosen as the single source of supply. Typical WSD results among four sources of test ball supply are given in Table 23.

3.1.2 BOCLE Mini-Round-Robin III Program

Mini-Round-Robin III was designed to evaluate the potential precision improvements with incorporation of the BOCLE test rings and SKF Sweden test balls. Five laboratories, given in Table 24, were to test four fuels, given in Table 25, using test rings from three different manufactured lots.

The BOCLE required modification to use the BOCLE test ring as shown in Figure 19.

ISOPAR M solvent was chosen as low-lubricity standard, and ISOPAR M solvent with 30 ppm DCI-4A corrosion inhibitor additive as the high-lubricity standard.

Details of the program are given in Appendix T.

3.1.3 BOCLE Mini-Round-Robin III Test Results

The interlaboratory range of test results from Mini-Round-Robin III are presented in Table 26, and the summary of the individual laboratory results are included in Appendix U. The data indicated that there was: (1) no difference among lots of test rings; (2) a significant difference in fuel types; (3) a difference among the laboratories with the clay-treated JP-4; and (4) an insignificant relationship with other interaction items.

The precision of the test, given in Table 27, improved significantly over that of Round-Robin II.

3.2 BOCLE ROUND-ROBIN III

3.2.1 BOCLE Round-Robin III Program

Round-Robin III was initiated to develop the required precision data for the improved test method. Twenty-one laboratories, as shown in Table 28, participated in the investigation.

There where nine fuels distributed of which two were rated high-volatility and seven low-volatility. Of these, two were classified as good-lubricity, four as medium-lubricity, and three as poor-lubricity. The test fuels are included in Table 29.

The Falex Corporation provided the test rings and the necessary mandrels to adapt to the cylinder configuration of the BOCLE units.

The BOCLE tests were to follow the details given in Appendix V.

3.2.2 BOCLE Round-Robin III Results

The individual laboratory Round-Robin III are given in Appendix W which includes data from two laboratories employing modified Exxon/Woodward BOCLE units. Each laboratory tested the fuels at 500-gram and 1000-gram loads. The data in Table 30, the average wear-scar diameters of all the laboratories, illustrates that the lubricity ranking of the nine test fuels remains the same for both test loads with one minor exception.

Exxon Research and Engineering Company determined the precision of the test method from the 320 data points available at each test load. The synopsis of the precision calculation is given in Table 31, and the detailed analysis in Appendix X. Analysis of the data proves that:

- The precision for the Exxon/Woodward units is comparable to that of the InterAv units.

- The exclusion of the two Jet A-1 test fuels, which were tested by only ten of the laboratories, did not materially affect the precision.

- The precision is changed little among tests run at 500-gram and 1000-gram test loads. A further illustration of this is given in Table 32 in which direct comparisons are made at three levels of lubricity.

The final draft of the Standard Test Method for Measurement of Lubricity of Liquid Hydrocarbon Fuels by the Ball-on-Cylinder Evaluator incorporates all the improvements which evolved during this investigation for a suitable test method to evaluate fuel lubricity, and is included in Appendix Y.

IV. CONCLUSIONS

1. The ball-on-cylinder lubricity evaluator (BOCLE) has proven its capability to adequately determine differences in lubricity among various fluids.

2. The BOCLE precision satisfies ASTM requirements as:

   Repeatability = 0.109 $(WSD)^{1.80}$

   Reproducibility = 0.167 $(WSD)^{1.80}$

   where WSD is the BOCLE wear-scar diameter, mm

3. Test humidity has a significant effect on the size of a wear scar generated during a ball-on-cylinder test, but machine design and test cylinder variability do not.

4. Most of the variability of the BOCLE test occurs in the generation of the wear scars and not in their measurement.

5. Test humidity, fuel volatility, and test machine design have a significant effect on BOCLE precision.

V. RECOMMENDATIONS

1. The test procedure in Appendix Y is ready for submission to the American Society for Testing and Materials (ASTM) to be considered as a standard test method. The inclusion of all pertinent details and a precision statement qualifies the method as a candidate for rapid acceptance by the fuels community.

2. Further study of the test materials and techniques should be investigated to improve the precision of this method.

3. The performance of jet engine fuel components should be correlated with the BOCLE test results on operational fuels.

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T A B L E S
AND
F I G U R E S

TABLE 1

EFFECT OF CHANGES IN FUEL COMPOSITION ON WEAR-SCAR DIAMETER

Fuel Number	1	2	3	4	5	6
Distillation End Point, °F	490	580	514	513	514	510
Aromatics, %	10.6	13.7	24.9	40.0	24.9	26.1
Olefins, %	0.8	1.1	1.9	1.9	1.9	8.4
Fuel Composition Changes	JP-5 base fuel	Aromatic compounds typical of those found in JP-5 added to base fuel	Naphthalenes increased to 4% and other aromatics added to base fuel	Aromatic compounds typical to those found in JP-5 added to base fuel	Dicyclic polynuclear aromatics added to base fuel	Aromatics and olefins typical of those found in JP-5 added to base fuel
WSD, mm	0.67	0.62	0.51	0.48	0.47	0.46

TABLE 2

EFFECT OF DISSOLVED OXYGEN ON LUBRICITY

Fuel	Atmosphere	Test Conditions*	Additives	WSD,mm
JP-5	Air	-	-	0.30
	N_2	-	-	0.24
Clay-Filtered JP-5	Air	-	-	0.61
	N_2	-	-	0.22
	N_2	-	7.5 ppm (vol) dilinoleic acid	0.24
140 Solvent	Air	-	-	0.80
	Air	80% relative humidity	-	1.00(scuffing)
	N_2	-	-	0.27
	N_2	80% relative humidity	-	0.27
	N_2	600 g load	-	0.22
	N_2	-	50 ppm (vol) Hitec E515	0.25

*Variations from standard operating conditions

TABLE 3

EFFECT OF LARGE LOAD CHANGES ON LUBRICITY

Load	JP-5	WSD, mm Clay-filtered JP-5	140 Solvent
200	0.20	0.68	0.81
400	0.24	0.75	0.85
600	0.25	0.86	0.80
800	0.29	0.62	0.66
1000	0.30	0.60	0.76
1200	0.31	0.64	0.75
1400	-	-	0.85

TABLE 4

BOCLE ROUND-ROBIN I - OPERATING CONDITIONS

A. Load: 1000 g or 300 g depending upon severity of fuel

B. Speed: 240 RPM

C. Duration: 30 minutes

D. Fuel Volume: 45 ml

E. Test Fluid Temperature: 77 ± 3°F (25 ± 1.5°C) at beginning of test

F. Supply Air: <0.1 ppm hydrocarbons, <50 ppm water

G. Purge Air: 10% Relative Humidity, 77± 3°F (25 ± 1.5°C) temperature

H. Pretreatment of Fuel in Reservoir:

   a. Length: 15 minutes

   b. Purge Air Flow Rate: 8 SCFH bubbling over and through test fluid

I. Purge Air Flow During Test: 8 SCFH bubbling over test fluid

TABLE 5

BOCLE ROUND-ROBIN I PARTICIPANTS

Bendix	Sundstrand
US Navy	US Air Force
Chandler Evans	Pratt & Whitney - East Hartford
Exxon - USA	Pratt & Whitney - West Palm Beach
Exxon - England	

TABLE 6

TEST FLUIDS FOR ROUND-ROBIN I

Sample Number	Fluid	Lubricity	Volatility
1	Clay-Filtered Jet A	Poor	Low
2	Jet A	Good	Low
3	Clay-Filtered Jet B	Poor	High
4	Jet B	Poor	High
5	JP-7	Good	Low
6	Clay-Filtered JP-7	Poor	Low
7	MIL-C-7024B	Poor	Low
8	JP-4	Good	High
9	JP-5	Good	Low
10	70:30 Isooctane:Toluene*	Poor	High
11	Isooctane*	Poor	High
12	Dodecane + 2% 1-chloronapthalene*	Poor	Low
13	Dodecane + 8% 1-methyl-napthalene*	Good	Low

*Possible Reference Fuel

TABLE 7

BOCLE ROUND-ROBIN I RESULTS

WEAR-SCAR DIAMETER, mm

Laboratory		Sample Number 1	2	3	4	5	6	7	8	9	10	11	12	13
Chandler Evans	X_1	0.610	0.458	0.828	0.655	0.419	0.855(S)	0.653	0.400	0.520	0.565	0.931	0.815	0.528
	X_2	0.540	0.536	0.783	0.658	0.465	0.828(S)	0.610	0.468	0.436	0.538	0.703(S)	0.663	0.498
P&E E. Hartford	X_1	0.35	0.32	0.38	0.37	0.56	0.69	0.36	0.30	0.31	0.35	0.37	0.80	0.33
	X_2	0.36	0.43	0.38	0.53 0.59(R)	0.62	0.55	0.38	0.38	0.33	0.33	0.38	0.82	0.41
Exxon	X_1	0.47	0.49	0.87	0.42	0.47	0.817	0.48	0.32	0.38	0.53	0.50	0.58	0.38
	X_2	0.55	0.50	0.75	0.43	0.47	0.84	0.60	0.35	0.40	0.73	0.57	0.52	0.40
Bendix	X_1	0.499	0.355	0.470	0.521	0.311	0.748	0.728	0.295	0.461	0.601	0.621	0.704	0.450
	X_2	0.523	0.427	0.656	0.474	0.389	0.910	0.563	0.355	0.397	0.254 0.340(R)	0.688	0.723	0.424
P&W W. Palm	X_1	0.46	0.54	0.82	0.49	0.57	0.74	0.79	0.31	0.40	0.60	0.22	0.75	0.44
	X_2	0.52	0.60	0.79	0.58	0.52	0.76	0.69	0.34	0.40	0.24 0.48(R)	0.33	0.66	0.43
U.S.Air	X_1	0.45	0.57 0.58(R)	0.81	0.60	0.54	0.80	0.59 0.48(R)	0.52	0.54	0.63	0.41(S)	0.78	0.57
Force	X_2	0.51	0.71 0.72(R)	0.80	0.67	0.78 0.76(R)	0.73	0.81	0.58	0.53	0.55 0.66(R)	0.70 0.72(R)	0.74	0.50
U.S. Navy	X_1	0.56	0.35	0.77	0.45	0.47	0.59	0.39	0.31	0.36	0.65	0.58(S)	0.81	0.55
	X_2	0.44	0.43	0.57(S)	0.45	0.70	0.77(S)	0.47	0.29	0.35	0.67	0.72	0.81	0.41
Sund-Strand	X_1		0.44	0.97	0.58	0.66		0.47	0.39	0.40			0.79	0.58
ESSO-U.K.	X_1	0.325	0.45	0.85	0.45	0.45	0.65	0.50	0.35	0.35	0.375	0.375	0.75	0.40
	X_2	0.50	0.475	0.95	0.40	0.625	0.45	0.41	0.35	0.40	0.35	0.37	0.65	0.40

NOTES: X_1 = 1st Result, X_2 = 2nd Result, S = Scuffing during run, R = Repeat Run

TABLE 8

PROPERTIES OF CYLINDERS USED IN ROUND-ROBIN I PROGRAM

Laboratory		Cylinder Number	Hardness (Rockwell C)	Surface Finish (micro-inches CLA)	Outside Diameter (inches)	New Cyl. Calibration Using Sample #1 (Wear-Scar Diameter,mm)
Chandler Evans	1st Cylinder Used	-	20.0	3 - 4	1.765	-
	2nd Cylinder Used	-	21.5	2 - 3	1.766	-
	3rd Cylinder Used	-	20.0	3 - 4	1.766	-
Pratt & Whitney East Hartford	1st Cylinder Used	62	R_A 59	6.0	1.730	0.37
	2nd Cylinder Used	63	R_A 59	4.5	1.729	0.36
	3rd Cylinder Used	64	R_A 59	6.0	1.729	0.35
Exxon	1st Cylinder Used	43	20.4	5.0	1.80	0.40
	2nd Cylinder Used	45	20.4	4.5	1.80	0.43
	3rd Cylinder Used	50	20.6	5.0	1.80	0.47
	4th Cylinder Used	56	20.4	5.0	1.80	0.45
Bendix	1st Cylinder Used	3	18	4 - 9	1.7495	0.588
	2nd Cylinder Used	4	18	4 - 9	1.7495	0.346 0.501 (R)
	3rd Cylinder Used	5	18	4 - 9	1.7495	0.512
Pratt & Whitney West Palm Beach	1st Cylinder Used	-	20	4.5	1.741	0.66
	2nd Cylinder Used	-	22	5.5	1.742	0.54
	3rd Cylinder Used	-	20	6.0	1.738	0.43
US Air Force	1st Cylinder Used	127	26	4.3	1.7485	0.61
	2nd Cylinder Used	108	24	4.1	1.7520	0.52
	3rd Cylinder Used	147	26	4.8	1.7503	0.71
US Navy	1st Cylinder Used	37	21	6.0	1.748	0.45
	2nd Cylinder Used	13	20	8.5	1.748	0.52
	3rd Cylinder Used	38	21	8.5	1.744	0.50

TABLE 9

ANALYSIS OF ROUND-ROBIN I DATA

Number	Description	WSD, mm Average	Among Labs Std. Deviation	Within Labs Std. Deviation
1	Clay-Filtered Jet A	0.485	0.062	0.049
2	Jet A	0.478	0.094	0.058
3	Clay-Filtered Jet B	0.730	0.171	0.062
4	Jet B	0.509	0.092	0.052
5	JP-7	0.522	0.098	0.099
6	Clay-Filtered JP-7	0.705	0.116	0.081
7	MIL-C-7024B	0.564	0.136	0.085
8	JP-4	0.370	0.083	0.036
9	JP-5	0.410	0.069	0.030
10	70:30 Isooctane:Toluene	0.498	0.125	0.137
11	Isooctane	0.568	0.225	0.039
12	Dodecane +2% 1-choloro naphthalene	0.723	0.082	0.054
13	Dodecane +8% 1-methyl naphthalene	0.445	0.060	0.045

<u>Repeatability</u> - Duplicate results by the same operator should be considered suspect if they differ by more than the following amount: 0.196 mm

<u>Reproducibility</u> - The results submitted by each of two laboratories should not be considered suspect unless they differ by more than the following amount: 0.371 mm

TABLE 10

EFFECT OF FINAL RINSE ON WEAR-SCAR DIAMETER

Fuel	Wear-Scar Diameter, mm Final Rinse Isooctane		Test Fluid
JP-5	0.466		0.485
	0.440		0.446
	0.412		0.446
	0.452	Overall	0.416
Mean	0.443	0.445	0.448
Standard Deviation	0.023	0.024	0.028
Clay-	0.672		0.632
Filtered	0.559		0.692
JP-5	0.545		0.579
	0.612		0.725
Mean	0.597	0.627	0.657
Standard Deviation	0.058	0.065	0.065
140	0.825		0.805
Solvent	0.818		0.778
	0.800		0.791
	0.884		0.825
Mean	0.832	0.816	0.800
Standard Deviation	0.036	0.032	0.020

TABLE 11

BOCLE MINI-ROUND-ROBIN I RESULTS

WEAR-SCAR DIAMETER, mm

Company	Harpoon	JP-4	JP-5	Clay-Filtered JP-5
Exxon	0.925	0.440	0.560	0.705
	0.940	0.465	0.560	0.720
	0.915	0.420	0.560	0.655
Average	0.927	0.442	0.560	0.693
Standard Dev.	0.013	0.023	0.000	0.034
Sundstrand	0.805	0.355	0.505	0.610
	0.805	0.370	0.500	0.695
	0.790	0.360	0.440	0.605
Average	0.800	0.362	0.482	0.637
Standard Dev.	0.009	0.008	0.036	0.051
NAPC	0.815	0.350	0.490	0.570
	0.770	0.405	0.435	0.660
	0.785	0.420	0.515	0.605
Average	0.790	0.392	0.480	0.611
Standard Dev.	0.023	0.037	0.041	0.045
Pratt & Whitney	0.785	0.375	0.545	0.600
	0.775	0.390	0.480	0.495
	0.790	0.405	0.490	0.540
Average	0.783	0.390	0.505	0.545
Standard Dev.	0.008	0.015	0.035	0.053
Overall Average	0.825	0.396	0.507	0.622
Overall Standard Dev.	0.063	0.036	0.044	0.068

TABLE 12

BOCLE MINI-ROUND-ROBIN I SUMMARY FOR EACH FUEL

	THREE LABORATORIES*				FOUR LABORATORIES			
	WEAR-SCAR DIAMETERS mm							
FUEL	r	df	R	DF	r	df	R	DF
JP4	.059	24	.083	7	.058	32	.119	7
JP5	.096	24	.119	6	.082	32	.470	9
CFJP5	.122	24	.205	7	.109	32	.238	7
HARPOON	.037	24	.048	7	.040	32	.285	3
	WEAR-SCAR VOLUMES*10**(-6) CM**3							
FUEL	r	df	R	DF	r	df	R	DF
JP4	14	24	20	8	15	32	32	7
JP5	38	24	52	6	32	32	63	8
CFJP5	75	24	116	8	68	32	149	7
HARPOON	37	24	48	7	50	32	294	4

Repeatability (r) - A two-sided 95% confidence interval. Duplicate results by the same operator should be considered suspect if they differ by more than the given (r) for each fuel.

Reproducibility (R) - A two-sided 95% confidence interval. The results submitted by each of two laboratories should not be considered suspect unless they differ by more than the given (R) for each fuel.

*No EXXON data.

TABLE 13

BOCLE MINI-ROUND ROBIN II - SURFACE FINISH OF CYLINDERS

Lot Number	Cylinder Specification	Surface Finish
1A	AMS 6440	Ground to 4-9AA
1B	AMS 6440	Ground and lapped
2A	AMS 6444	Ground to 4-9AA
2B	AMS 6444	Ground and lapped

TABLE 14

MEAN BALL WEAR-SCAR RESULTS

Cylinder Laboratory	Reference Fuel 40	40L	44	44L	Test Fuel 40	40L	44	44L
Pratt & Whitney	.8213		.7938		.4375		.4188	
US Air Force		.68		.775		.28		.3037
Sundstrand	.820	.7725			.415	.34		
Exxon Research & Engineering			.665	.665			.3563	.3463
US Navy	.820			--	.3675			.350
Southwest Research Institute		.685	.8038			.3363	.4275	
Average Mean WSD	.8204	.7125	.7542	.720	.4067	.3188	.4009	.3333

TABLE 15

BOCLE ROUND-ROBIN II PARTICIPANTS

LABORATORY	EXXON/WOODWARD APPARATUS	INTERAV APPARATUS
Allied/Bendix	X	
Woodward Governor	X	
Exxon Research & Engineering	X	
Naval Air Propulsion Center	X	X
Esso Petroleum	X	
Sundstrand	X	
Lucas	X	
Chandler Evans	X	
Southwest Research Institute		X
Mountain Home AFB		X
Hill AFB		X
Mukilteo AFB		X
ALC/SFQLA		X
AFWAL/POSF		X
Pratt & Whitney		X
Thornton		X
Ethyl		X

TABLE 16

BOCLE ROUND-ROBIN II TEST FLUIDS

Sample Number	Fuel Type	Volatility	Lubricity Level
83-POSF-1431	Shale JP-4	High	High
83-POSF-0988	Petroleum JP-4	High	Medium
84-POSF-0708	2X Clay-Filtered Petroluem JP-4	High	Medium
84-POSF-1775	2X Clay-Filtered Shale JP-4	High	Low
84-POSF-2071	JP-5	Low	High
83-POSF-0709	Jet A1	Low	Medium
83-POSF-0878	JP-7	Low	Medium
83-POSF-0847	Decalin	Low	Low

TABLE 17

BOCLE ROUND-ROBIN II - EXXON/WOODWARD
WEAR SCAR DIAMETER RESULTS

	BENDIX	WOODWARD GOVERNOR	EXXON R&E	NAPC	ESSO PETROL*	SUNDSTRAND	LUCAS**	CECO
1431	.28	.29	.30	.35	.35	.31	.30	.35
	.36	.30	.31	.32	.34	.31	.33	.34
0988	.32	.30	.33	.29	.40	.31	.29	-
	.30	.30	.30	.35	.38	.30	.30	.34
0708	.38	.46	.44	.45	.56	.32	.80	.40
	.40	.43	.44	.43	.54	.32	.68	.50
1775	.72	1.08	.90	Scuff	1.06	.82C	.28T	.89
	.62	1.20	1.30	Scuff	1.14	.82	.28T	.88
2071	.34	.31	.32	.35	.37	.30	-	.32
	.36	.32	.32	.33	.36	.30	-	.32
0709	.32	.33	.37	.44	.38	.36	.42	.47***
	.34	.36	.34	.44	.35	.34	.42	.45***
0878	.43	.63	.68	.82	.60	.55	.79	
	.56	.68	.73	.53	.71	.54	.90	
0847	.68	.82	.86	Scuff	1.05	.76	.61T	
	.74	.85	1.04	Scuff	1.05	.80C	.62T	
2071(10)	.36		.34	.37	.39			
2071(50)	.59		.36	.40	.40			
			.33	.37				
0847(10)	.60		1.11	.77	.91			.72
								.77
0847(50)	.76		1.03	Scuff	.98			
	.68		1.08	Scuff				
1431(10)		.31				.30	.29	
1431(50)		.31				.30	.33	.44
		.38				.33	.28	
1775(10)		.96				.65	.46T	
1775(50)		1.18				.95C	.64T	S
		1.21				.92C	.32T	

* Standard tests at 50-56% RH - Extra tests at 64-64.5% RH
** Standard tests at 35-45% RH - Extra tests at 40-47% RH
*** Cylinder tracks ran together

C Loud Chatter
S Wear Scar too large to read
T Load 300 grams

TABLE 18

BOCLE ROUND-ROBIN II - INTERAV WEAR-SCAR
DIAMETER RESULTS

	SWRI	Mt. Home AFB-A	P&W	NAPC	Thorton	Hill AFB-B	Mukilteo AFB-C	Quality Control AFB-D	AFWAL	Edwin Cooper
1431	.40	.31	.34	.35	.31	.32	.33	.33	.34	.32
	.36	.30	.32	.39	.31	.32	.32	.33	.34	.32
0988	.32	.29	.34	.35	.33	.32	.31	.36	.34	.29
	.33	.32	.34	.35	.32	.33	.32	.36	.34	.28
0708	.50	.48	.47	.44	.51	.44	.48	.49	.48	.42
	.48	.48	.48	.43	.51	.44	.48	.50	.48	.48
1775	.51	.72	.92	.64	.85	.85	.70	.96C	.88	.72
	.54	.84	.84	.53	1.10S	.82	.70	.90N	.87	.80
2071	.30	.32	.32	.37	.31	.38	.35	.35	.34	.32
	.34	.33	.31	.35	.31	.37	.35	.34	.34	.32
0709	.48	.34	.46	.37	.37	.40	.43	.43	.39	.43
	.43	.34	.44	.37	.40	.40	.42	.40	.40	.50
0878	.67	.52	.61	.66	.54	.58	.54	.56	.58	.52
	.68	.83	.86	.61	.54	.58	.52	.54	.57	.56
0847	.47	.81	.80	.77	1.24S	.78	.79	.94G	.80	.71
	.62	.76	.80	.61	.79	.74	.82	.88N	.95G	.80
2071(10)	.32			.36	.31	.36		.34		
2071(50)	.50			.35	.41	.39		.41		
	.43			.37	.37	.40		.39		
0847(10)	.50			S	1.01S	.78		.87		
				S						
0847(50)	.56			.94	1.04S	.82		.92		
	.50				.96S	.88		.82		
1431(10)		.30	.36				.30		.34	
1431(50)		.31	.37				.32		.35	
		.35	.37				.36		.34	
1775(10)		.77	.80				.75		.84G	
1775(50)		.98	Scuff				.92		1.12	
		1.10	Scuff				.88		1.21G	

C Loud Chatter
G Grinding
N Excessive noise
L Loud Screech
s Scuff

TABLE 19

BOCLE ROUND-ROBIN II VARIABLES AFFECTING PRECISION

Variable	Level	Degrees of Freedom	Mean Square Error s	Ratio s_2/s_1	Confidence Level, %
Test Machine	InterAv	80	0.0333	2.13	99
	CRC	44	0.0710		
Test Humidity	10%	56	0.0193	3.59	95
	50%	18	0.0694		
Fuel Volatility	Low	28	0.0256	2.02	95
	High	28	0.0517		

TABLE 20

BOCLE ROUND-ROBIN II WEAR-SCAR DIAMETER
MEASUREMENT PROGRAM

Number	EXXON		COLT		P&W		SUNDSTRAND		BENDIX		WOODWARD		WPAFB
1	0.31	0.31	0.31	0.31	0.30	0.30	0.29	0.30	0.32	0.29	0.31	0.31	0.32
2	.34	.34	.35	.35	.35	.35	.33	.34	.32	.34	.24	.35	.35
3	.33	.33	.33	.33	.34	.34	.32	.32	.32	.30	.33	.34	.34
4	.35	.35	.36	.36	.36	.36	.36	.35	.34	.34	.35	.37	.37
5	.32	.32	.35	.36	.34	.34	.33	.32	.31	.34	.33	.34	.35
6	.28	.28	.28	.27	.26	.26	.25	.25	.31	.29	.26	.26	.28
7	.40	.41	.43	.43			.45	.49	.40	.42	.44	.45	.44
8	.45	.45	.47	.47			.47	.47	.43	.45	.48	.48	.48
9	.53	.54	.57	.57			.58	.57	.55	.56	.59	.59	.58
10	.50	.50	.54	.54			.57	.54	.53	.53	.55	.56	.56
11	.46	.46	.47	.47			.48	.45	.45	.47	.50	.49	.49
12	.52	.52	.54	.54			.51	.52	.46	.45	.56	.56	.55
13	.69	.69	.77	.76	.73	.73	.71	.70	.66	.66	.75	.75	.73
14	1.10	1.08	-	-	1.00	1.05	1.01	1.02	1.03	.99	.78	.78	1.10
15	.79	.79	.87	.87	.84	.84	.82	.81	.79	.78	.85	.84	.84
16	.90	.90	-	-	.88	.89	.82	.82	.84	.84	.90	.89	.95
17	.85	.86	.92	.92	.89	.88	.88	.87	.79	.81	.92	.91	.88
18	.99	1.00	-	-	1.02	.97	.90	.95	.99	.96	1.06	.96	1.06

Number	NAPC		INTERAV		SWRI		HILL		MT. HOME		MUKILTEO	
1	0.32	0.32	0.31	0.30	0.29	0.29	0.31	0.30	0.30	0.30	0.31	0.31
2	.36	.36	.34	.34	.34	.34	.35	.37	.35	.35	.35	.35
3	.33	.35	.33	.33	.32	.32	.34	.33	.32	.32	.33	.32
4	.37	.37	.35	.34	.35	.34	.37	.36	.36	.36	.35	.36
5	.35	.35	.35	.34	.34	.34	.36	.33	.34	.34	.35	.35
6	.26	.28	.27	.27	.26	.26	.28	.26	.26	.26	.25	.26
7	.43	.43	.44	.44	0.44	0.44	0.45	0.44	0.48	0.44	0.44	.46
8	.46	.46	.47	.47	.46	.46	.49	.49	.46	.48	.46	.47
9	.45	.56	.58	.57	.58	.48	.57	.58	.57	.56	.59	.58
10	.54	.55	.56	.55	.55	.55	.59	.62	.56	.57	.57	.56
11	.48	.48	.47	.47	.49	.49	.48	.50	.48	.48	.48	.48
12	.54	.54	.54	.54	.54	.54	.57	.56	.54	.55	.56	.56
13	.72	.71	.73	.72	.72	.72	.73	.72	.70	.72		
14	-	-	1.05	1.06	1.00	1.02	1.03	1.00	1.12	1.12		
15	.83	.82	.83	.83	.82	.83	.83	.85	.88	.84		
16	.92	.91	.88	.89	.88	.84	.91	.83	.84	.92		
17	.88	.88	.87	.87	.88	.88	.87	.90	.89	.88		
18	1.03	1.02	1.00	1.01	.98	.98	1.01	.99	1.06	1.04		

TABLE 21

TEST CYLINDER EVALUATION - TEST CYLINDER/TEST RING

Cylinder	Surface Finish, μin.	Mean for 5 fuels $\bar{\Delta}$	Mean for 5 fuels $\bar{\sigma}$	Reproducibility - 3 cylinders Max difference in means Cal fl	JP-4	JP-7	CP JP-4	JP-8
Falex	4 to 9	0.111	0.048	0.054	0.053	0.194	0.013	-
Jayna	16 to 22	0.075	0.034	0.056	0.094	0.036	0.043	-
Timken ring	20 to 30	0.014	0.009	0.006	0.013	0.005	0.032	0.007

Note: 5 fuels
3 runs per fuel
3 cylinder types
3 cylinders per type

TABLE 22

REPRODUCIBILITY AMONG BOCLE TEST RING LOTS

Wear-Scar diameter, mm

	ISOPAR M + DCI-4A	JP-4	JP-8	JP-7	C.T. JP-4
Lot Average:					
K	0.496	0.547	0.551	0.683	0.905
L	0.499	0.551	0.559	0.685	0.913
M	0.506	0.556	0.559	0.687	0.933
MX	0.516	0.553	0.553	0.681	0.916
All runs $\bar{x}$	0.504	0.552	0.556	0.684	0.917
All runs sd	0.015	0.012	0.011	0.011	0.021
Lot-lot max Δ*	0.020	0.009	0.008	0.006	0.028

*Calculated on average value for each lot

TABLE 23

TEST BALL SOURCE EVALUATION

Wear-scar diameter, mm

Fuel Type	Run	Falex	Atlas	Swedish	Winstead
JP-4	$\bar{x}$	0.562	0.558	0.548	0.447
	sd	0.003	0.013	0.013	0.013
JP-7	$\bar{x}$	0.693	0.685	0.683	0.450
	sd	0.003	0.009	0.008	0.010
CT JP-4	$\bar{x}$	0.922	0.910	0.920	0.710
	sd	0.025	0.013	0.005	0.013
ISOPAR M	$\bar{x}$	0.507	0.510	0.483	0.392
+ DCI-4A	sd	0.006	0.000	0.033	0.021

Note: (1) Winstead balls consistently lower WSD values.
(2) Winstead balls cannot differentiate between JP-4 and JP-7.

TABLE 24

BOCLE MINI-ROUND-ROBIN III PARTICIPANTS

AFWAL/POSF

Chevron Research Company

Rolls Royce Ltd.

Pratt & Whitney

Woodward Governor

TABLE 25

BOCLE MINI-ROUND-ROBIN III TEST FLUIDS

JP-4 Fuel

Clay-Treated Shale JP-4 Fuel

Isopar M *

Isopar M + 30 PPM DCI-4A **

* Available from EXXON Company, P.O. Box 2180, Houston, Texas 77001

** Available from E. I. DuPont de Nemours, 1007 Market Street, Wilmington, Delaware 19893

TABLE 26

BOCLE MINI-ROUND-ROBIN III INTERLABORATORY RANGE OF TEST RESULTS

Fuel Type	Range
Isopar M + DCI-4A	0.028
JP-4	0.017
Neat Isopar M	0.041
CT JP-4	0.157

*Based on mean laboratory values

TABLE 27

BOCLE MINI-ROUND-ROBIN III PRECISION

RR D-2-1007 precision data for ASTM methods

- Inclusive of all fuel types

Repeatability,	r = 0.042
Reproducibility,	R = 0.262

- Exclusive of CT JP-4

Repeatability,	r = 0.035
Reproducibility,	R = 0.108

TABLE 28

BOCLE ROUND-ROBIN III PARTICIPANTS

Air Force

- Hill AFB
- Holloman AFB
- MacDill AFB
- Mountain Home AFB
- Mukilteo AFB
- Wright-Patterson AFB

Allied Bendix

British Petroleum

Chevron Research Company

Esso Research

Ethyl Petroleum

InterAv Inc.

German Ministry of Defense

Naval Air Propulsion Center

Petro-Canada

Pratt & Whitney

Rolls Royce Ltd.

Shell Research

Southwest Research Institute

Sundstrand Aviation

Woodward Governor

TABLE 29

BOCLE ROUND-ROBIN III TEST FLUIDS

Jet A Fuel

Jet A-1, U.K. 1

Jet A-1, U.K. 2

Clay-Treated Jet A

JP-4 Fuel

Clay-Treated JP-4

JP-5 Fuel

JP-7 Fuel

ISOPAR M Solvent

TABLE 30

BOCLE ROUND-ROBIN III RESULTS

RANKING OF TEST FLUIDS

	500 G LOAD		1000 G LOAD	
FUEL TYPE	AVG WSD	SD	AVG WSD	SD
JP-4	0.491	0.024	0.558	0.025
JET A	0.498	0.020	0.563	0.022
JP-5	0.512	0.023	0.588	0.016
UK #1	0.595	0.019	0.668	0.028
UK #2	0.694	0.024	0.759	0.026
CT JP-4	0.718	0.053	0.813	0.059
ISOPAR M	0.726	0.037	0.849	0.050
CT JET A	0.731	0.048	0.822	0.037
JP-7	0.782	0.054	0.898	0.037

TABLE 31

BOCLE ROUND-ROBIN III PRECISION AT TWO TEST LOADS

	Repeatability	Reproducibility
I) 500-GRAM LOAD		
ALL DATA	$.12471 * X^{1.93}$	$.22687 * X^{1.93}$
EXCLUDING SAMPLES UK1 & UK2	$.13206 * X^{1.96}$	$.23782 * X^{1.96}$
EXCLUDING LABS B & F	$.11586 * X^{1.86}$	$.21973 * X^{1.86}$
EXCLUDING SAMPLES UK1 & UK2, EXCLUDING LABS B & F	$.12288 * X^{1.89}$	$.23229 * X^{1.89}$
EXCLUDING ALL LABS WHICH DID NOT TEST SAMPLES UK1 & UK2	$.10368 * X^{1.86}$	$.17093 * X^{1.86}$
II) 1000-GRAM LOAD		
ALL DATA	$.10946 * X^{1.80}$	$.16673 * X^{1.80}$
EXCLUDING SAMPLES UK1 & UK2	$.11868 * X^{1.87}$	$.17620 * X^{1.87}$
EXCLUDING LABS B & F	$.10697 * X^{1.72}$	$.15899 * X^{1.72}$
EXCLUDING SAMPLES UK1 & UK2, EXCLUDING LABS B & F	$.11710 * X^{1.80}$	$.16878 * X^{1.80}$
EXCLUDING ALL LABS WHICH DID NOT TEST SAMPLES UK1 & UK2	$.092495 * X^{1.84}$	$.11721 * X^{1.84}$

TABLE 32

BOCLE ROUND-ROBIN III RESULTS

EFFECT OF LOAD ON PRECISION

LEVEL OF LUBRICITY (WSD)	500 G		1000 G	
	REPEATABILITY	REPRODUCIBILITY	REPEATABILITY	REPRODUCIBILITY
0.50	0.03	0.06	0.03	0.05
0.69	0.06	0.11	0.06	0.08
0.92	0.11	0.19	0.09	0.14

FIGURE 1
EFFECT OF BLENDING FUELS ON LUBRICITY

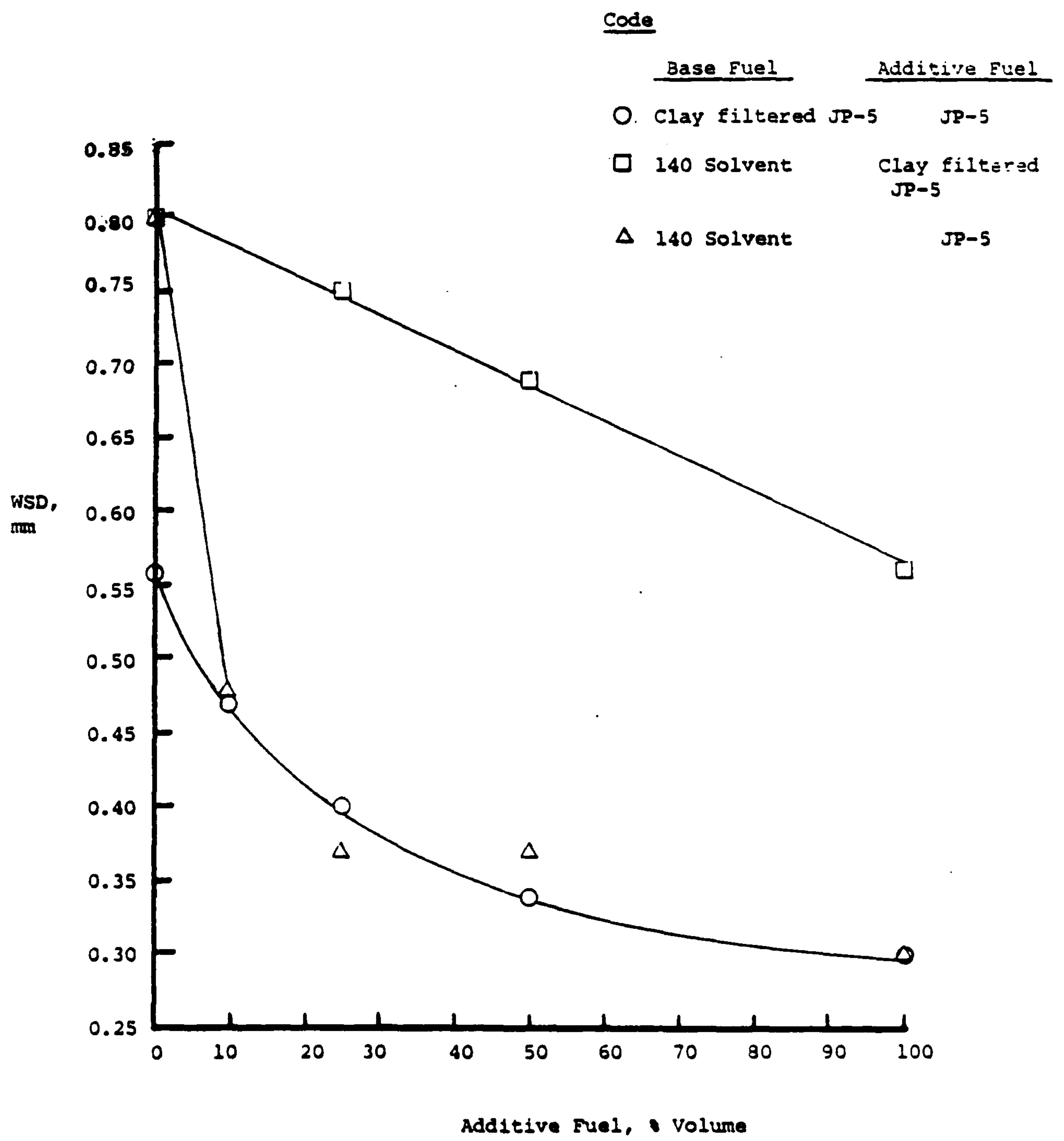


FIGURE 2

EFFECT OF HUMIDITY ON WEAR-SCAR DIAMETER

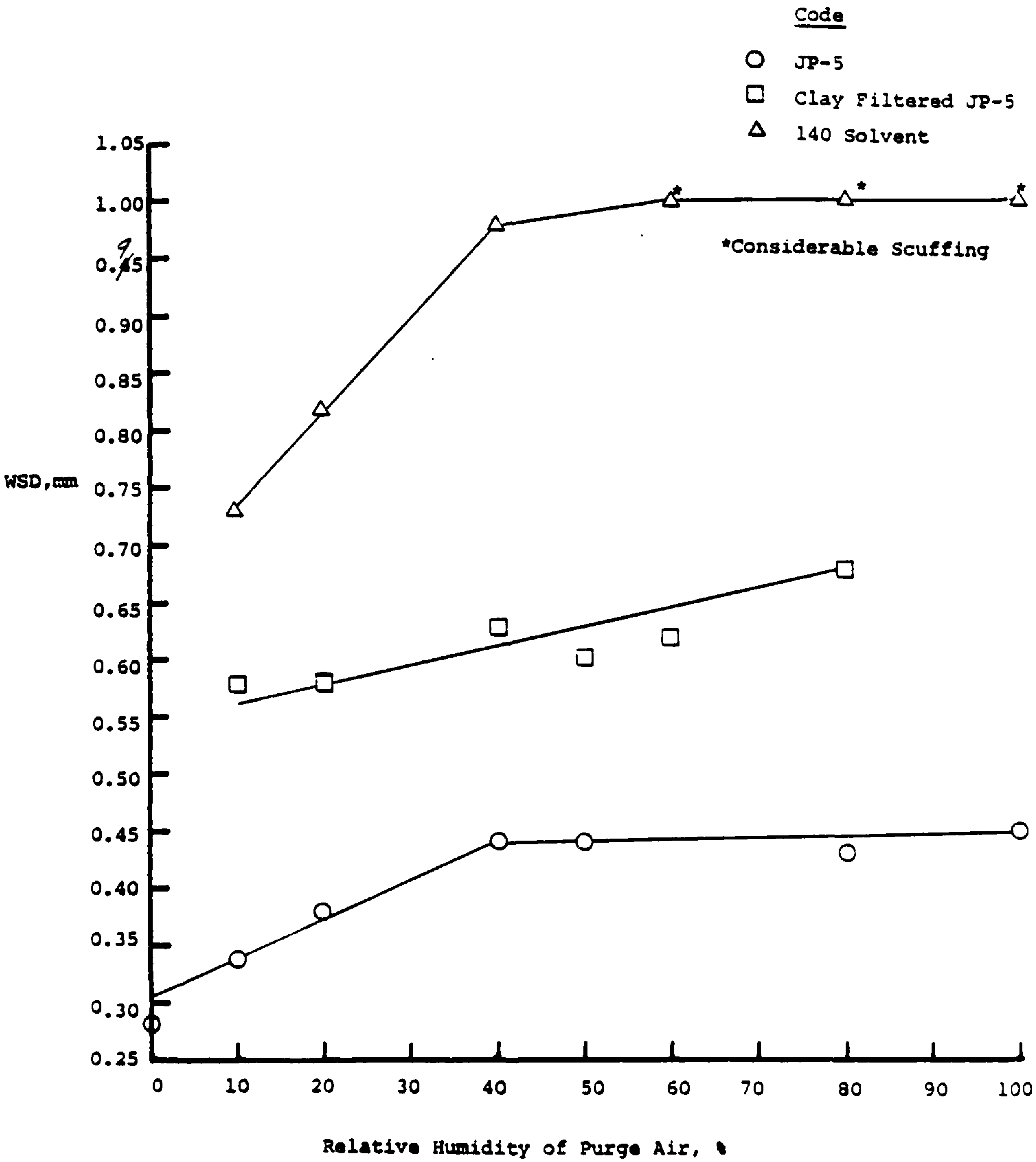


FIGURE 3
PERFORMANCE OF TWO DIFFERENT FUELS
IN AIR ATMOSPHERE

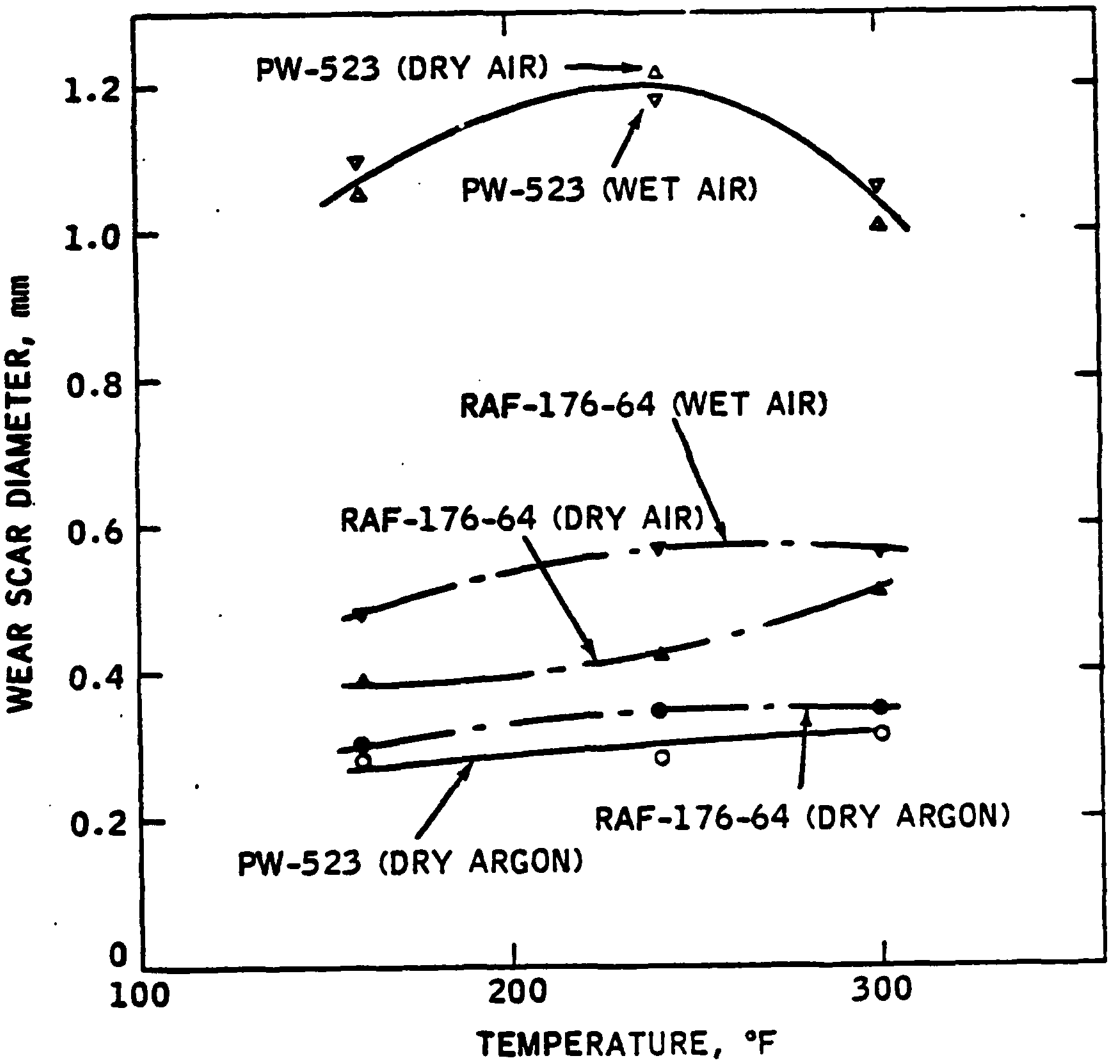


FIGURE 4

EXXON/WOODWARD BALL-ON-CYLINDER LUBRICITY EVALUATOR

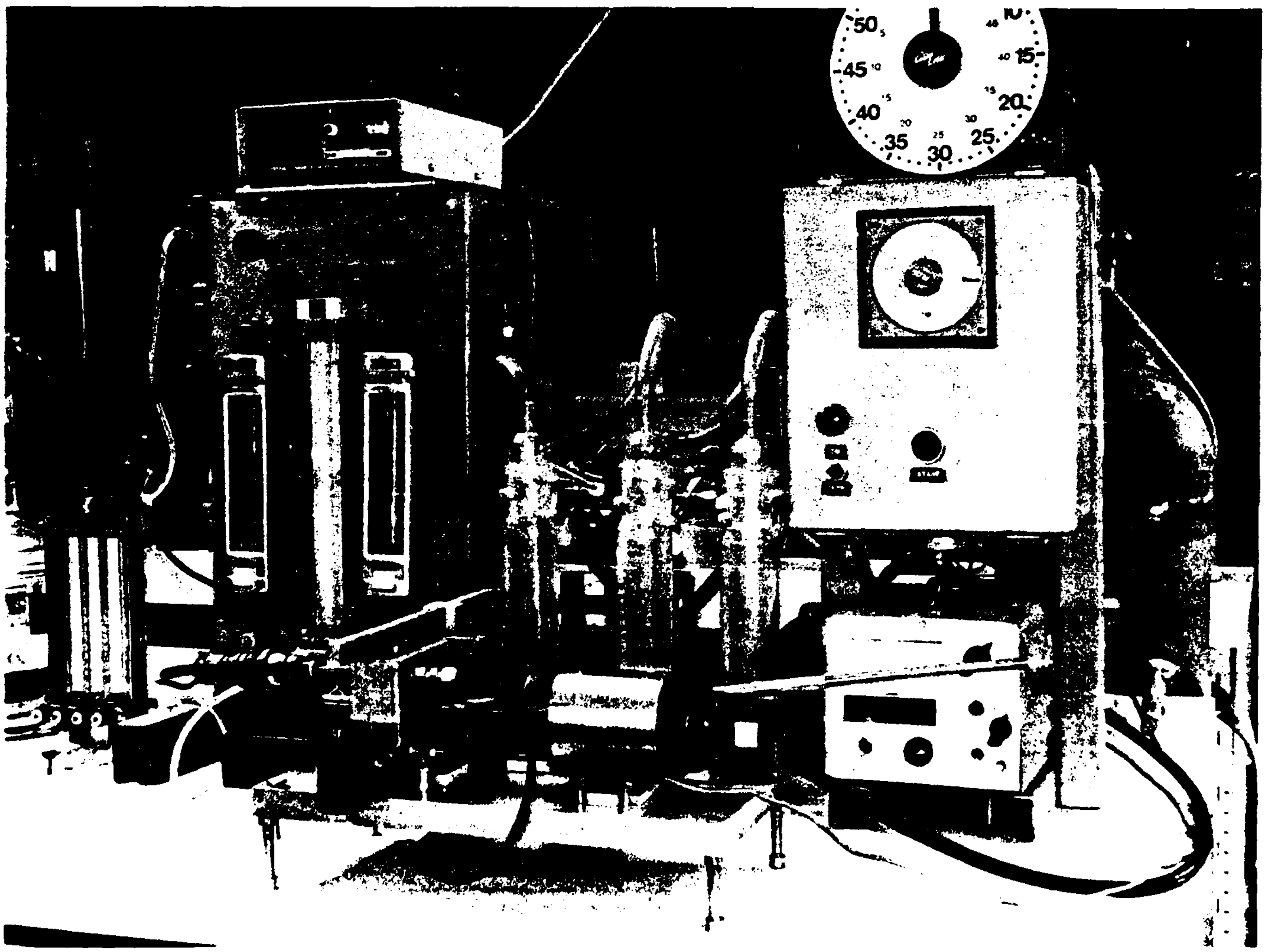


FIGURE 5

SCHEMATIC OF BALL-ON-CYLINDER LUBRICITY EVALUATOR (BOCLE)

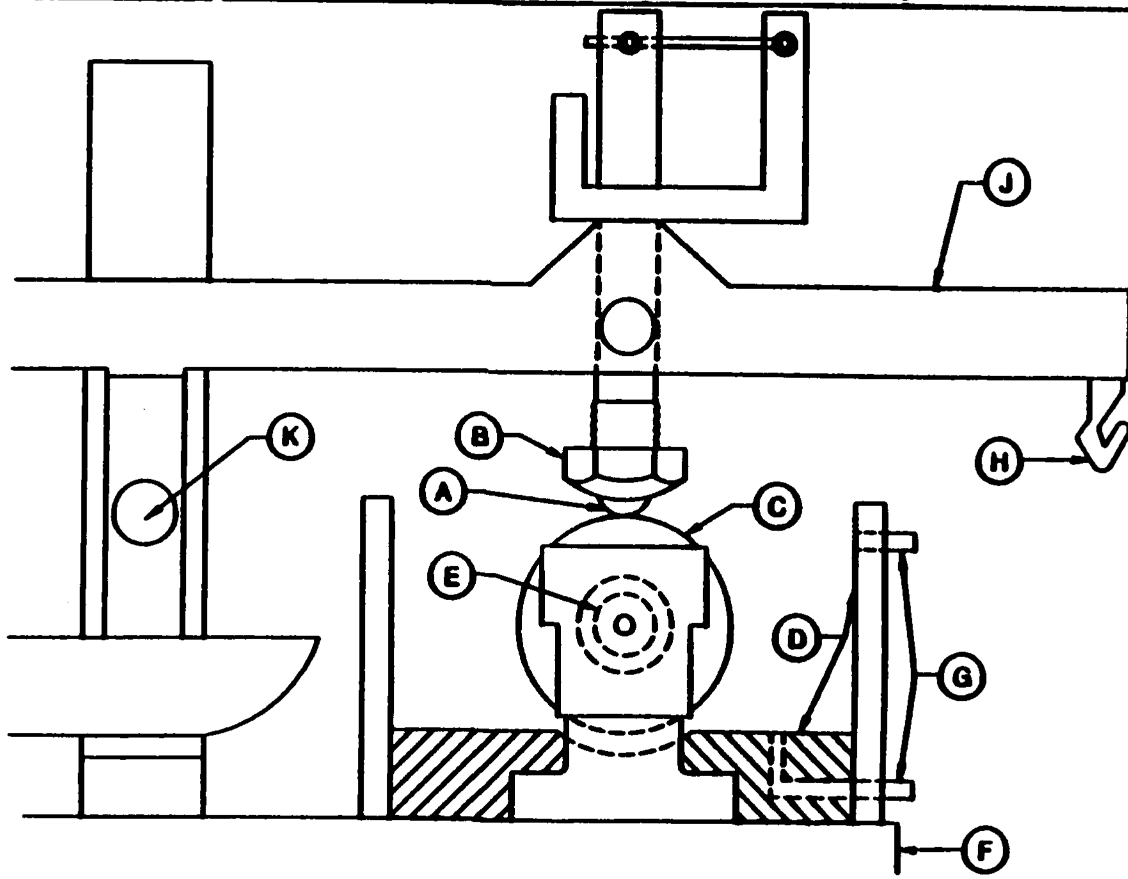


FIGURE 6

SCHEMATIC OF ATMOSPHERE CONTROL UNIT

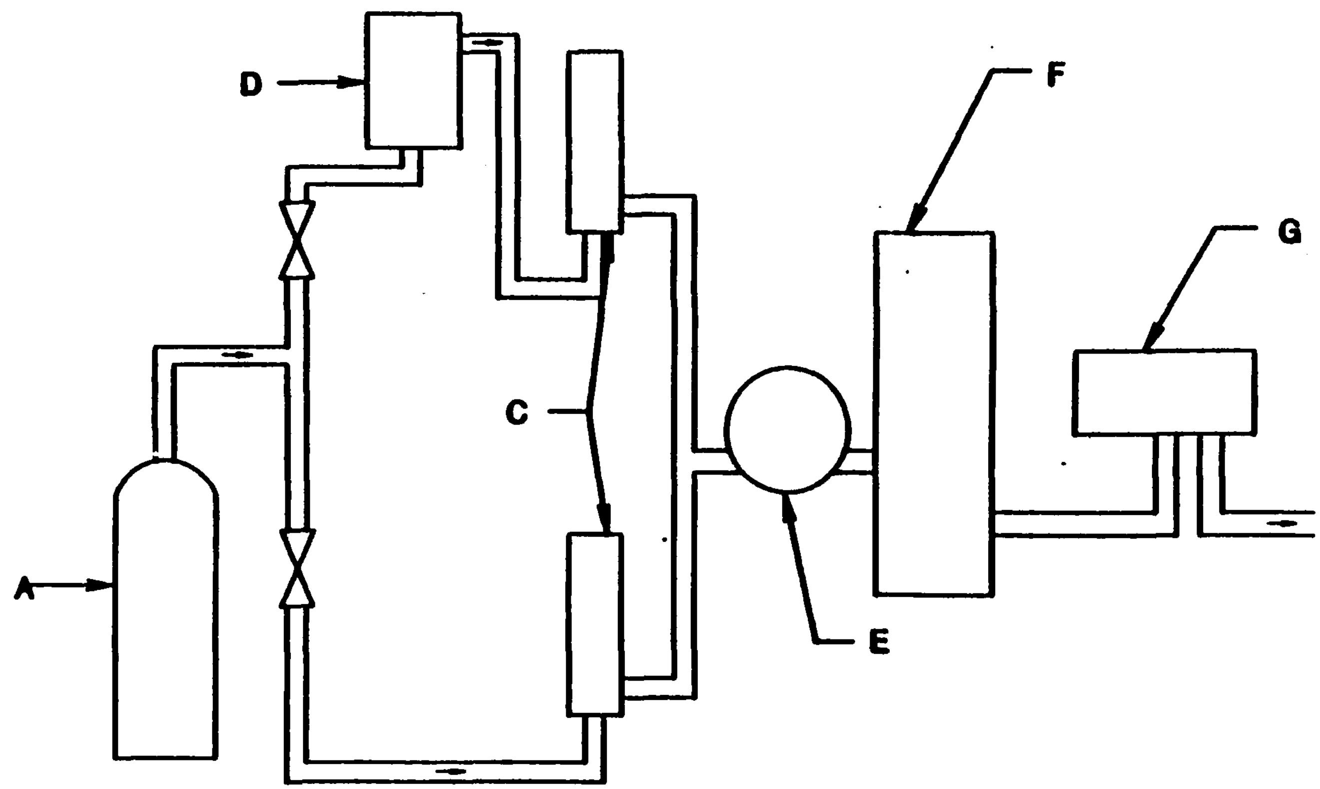


FIGURE 7

INTERAV BALL-ON-CYLINDER LUBRICITY EVALUATOR

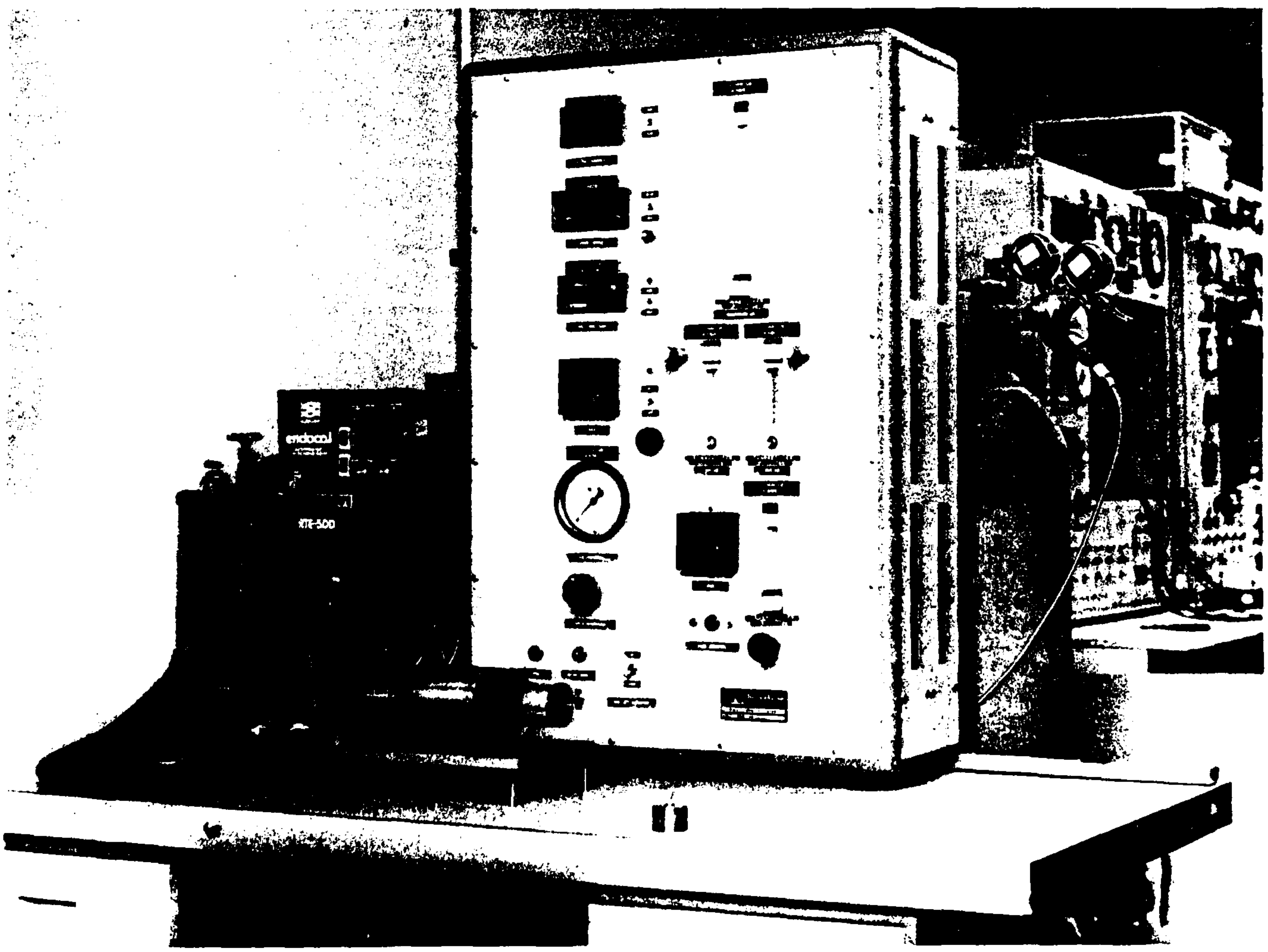


FIGURE 8

EFFECT OF TEMPERATURE ON WEAR-SCAR

OF JP-5 FUEL

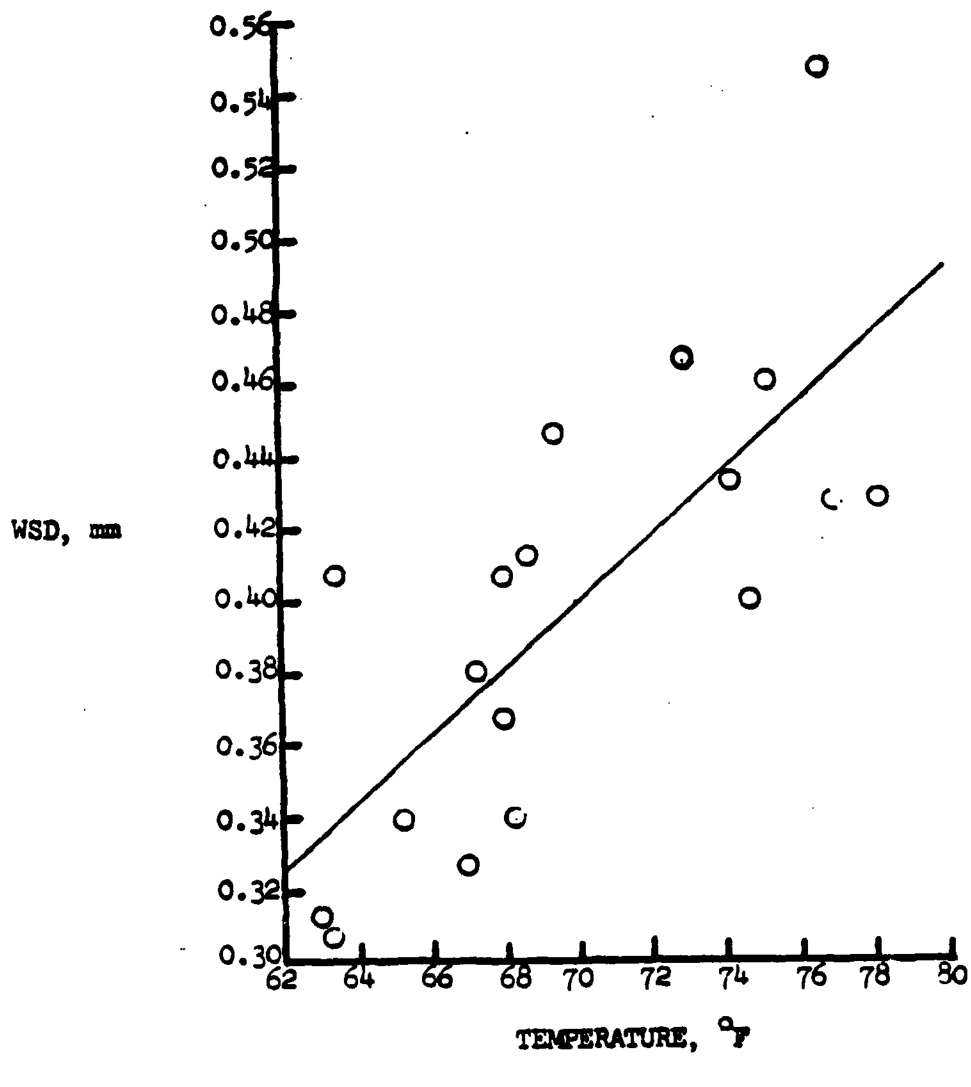


FIGURE 9

BOCLE ROUND ROBIN II RESULTS

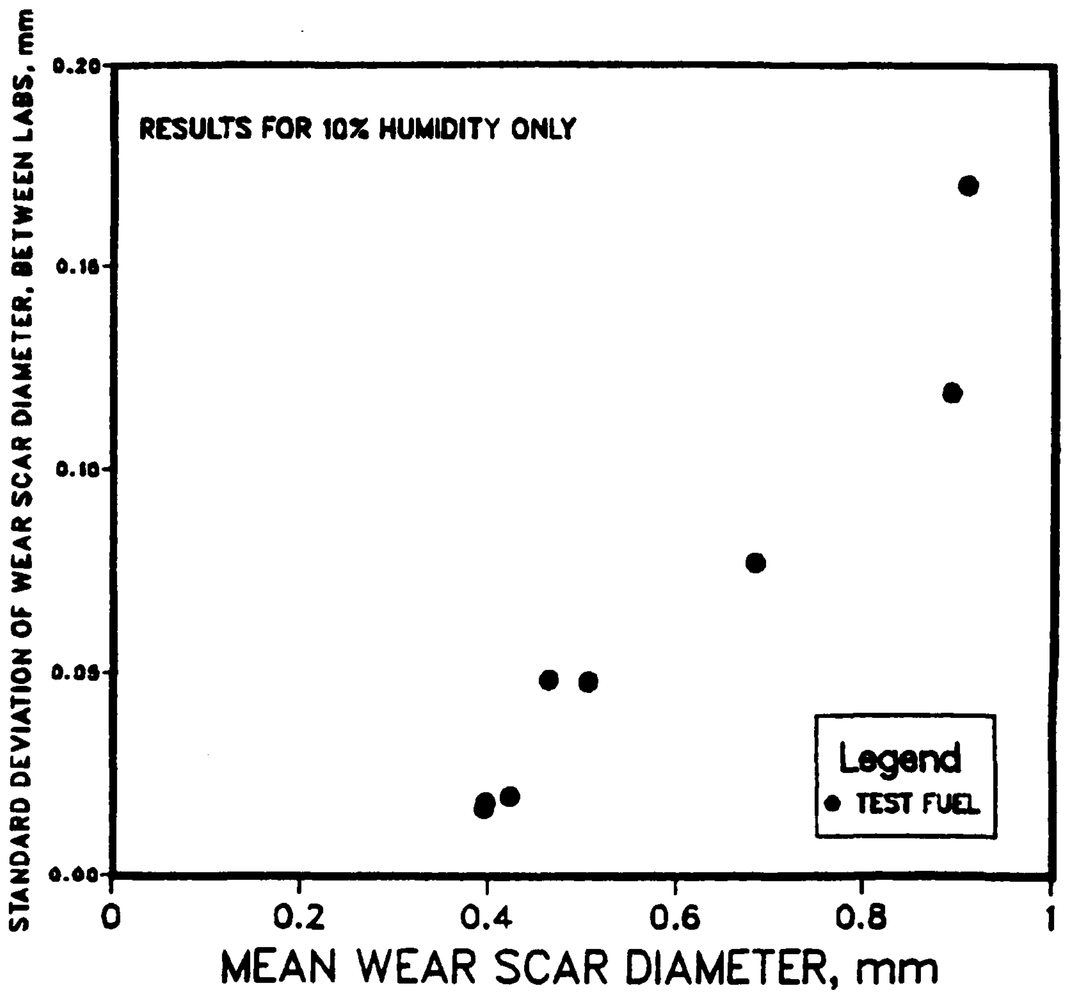


FIGURE 10

BOCLE ROUND ROBIN II

LUBRICITY PARAMETER = $(1/\text{WEAR SCAR DIAMETER})^{5/4}$

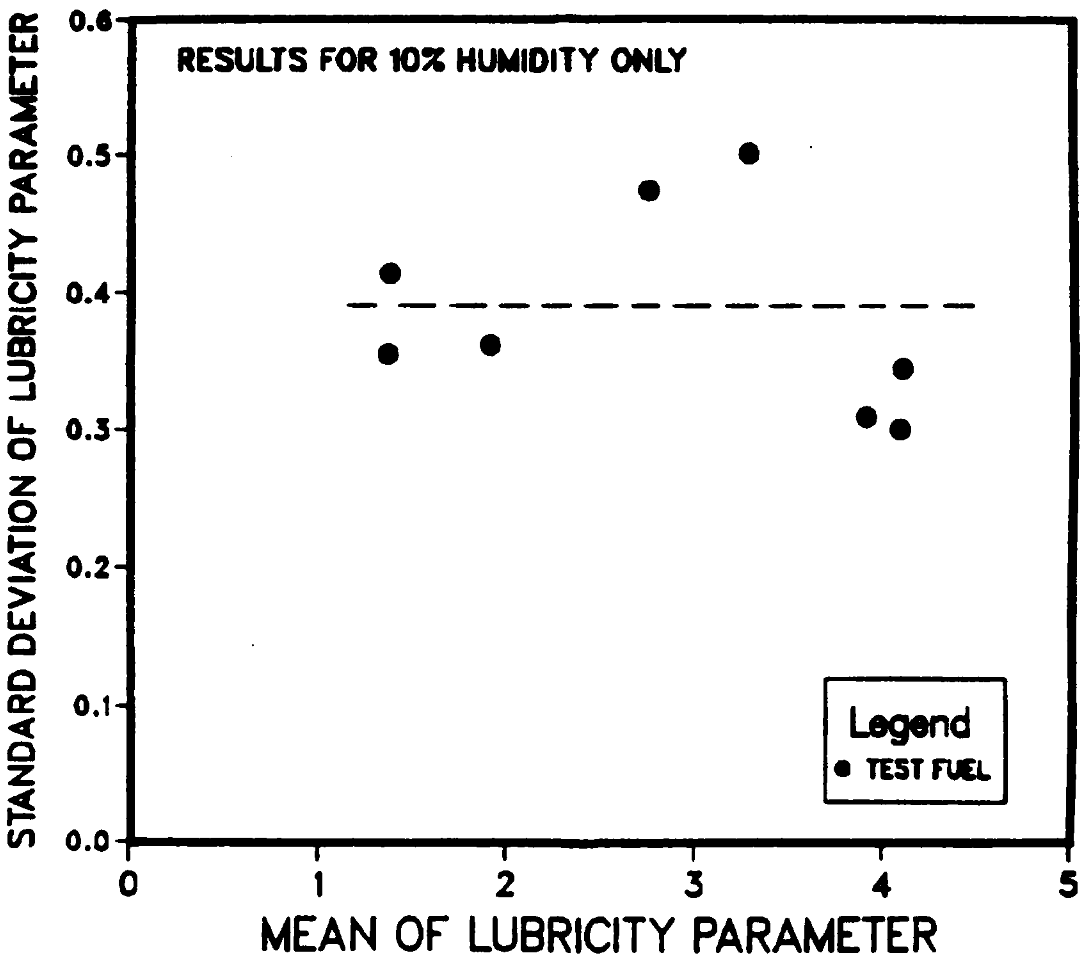


FIGURE 11

BOCLE ROUND ROBIN II PRECISION

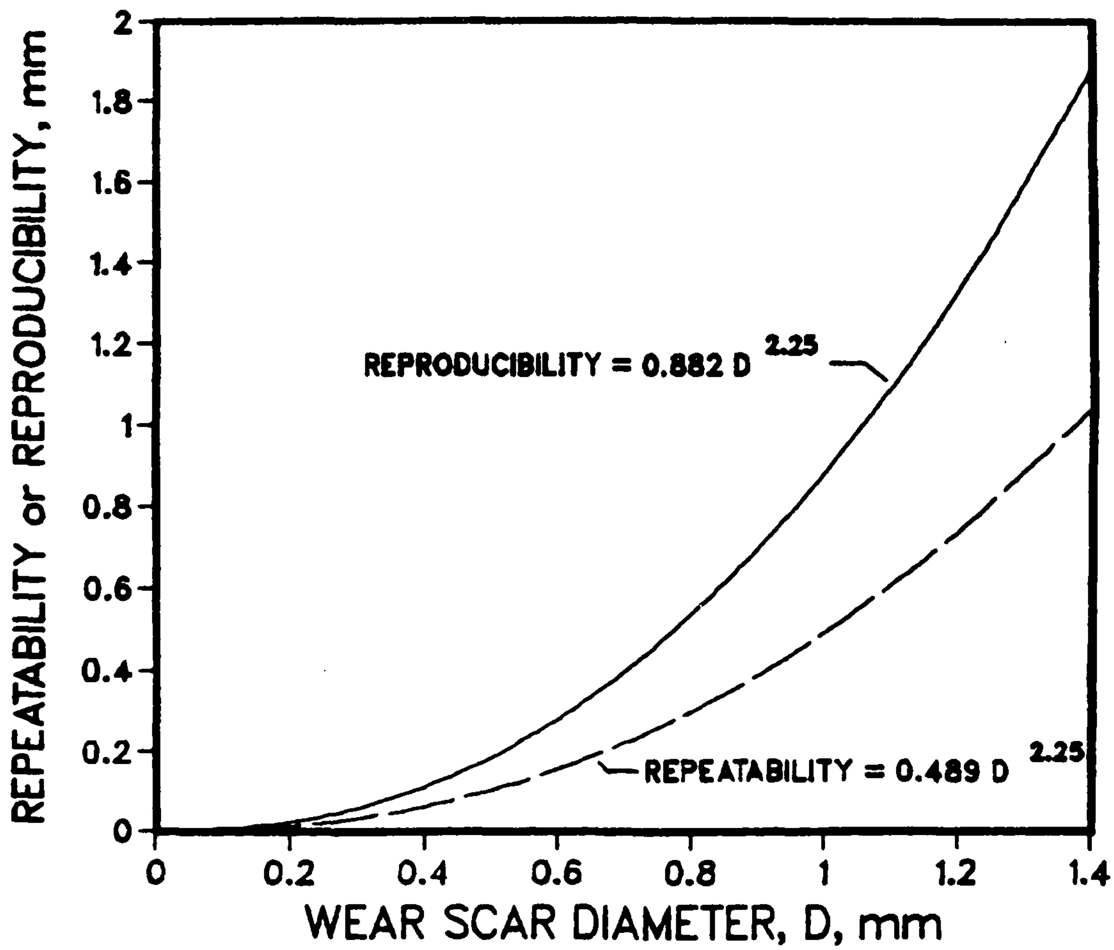


FIGURE 12

BOCLE ROUND ROBIN II

RESULTS FOR TWO TYPES OF MACHINES

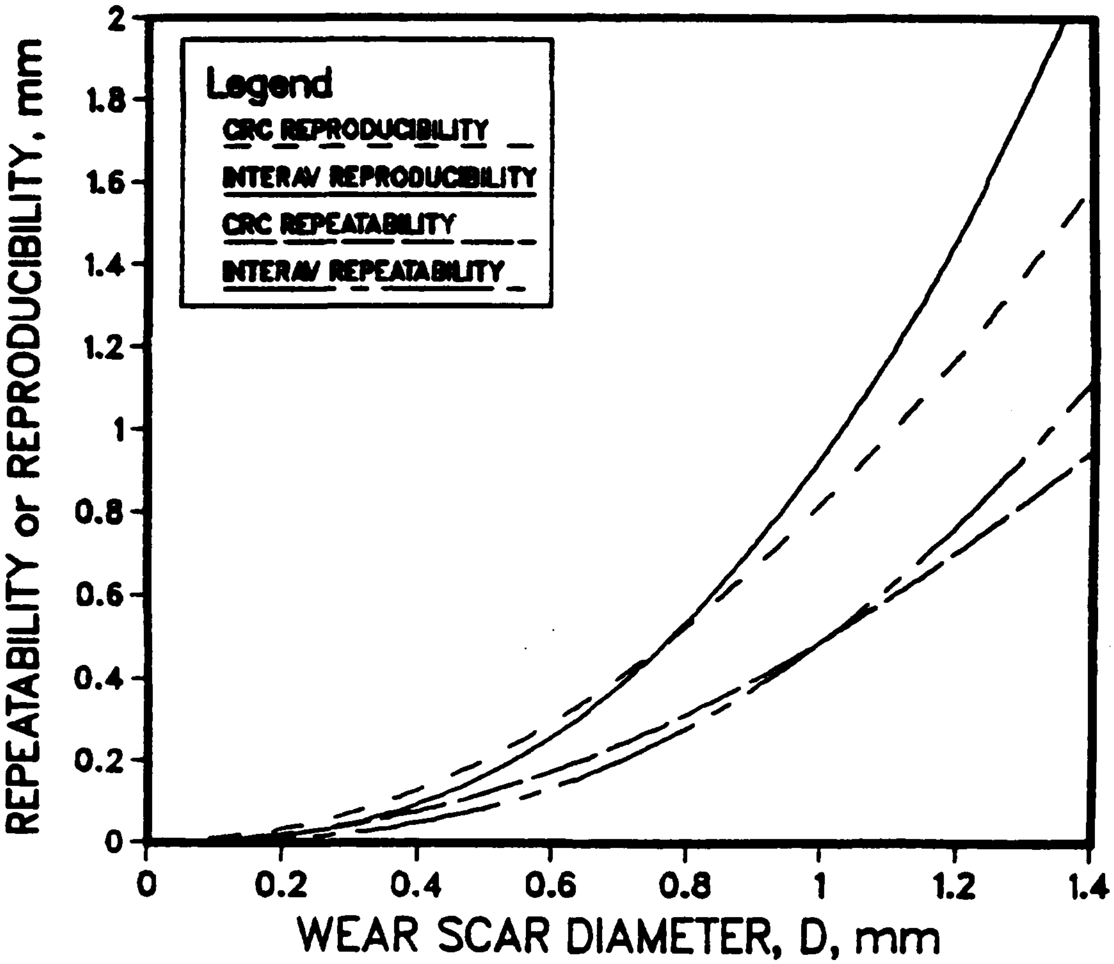


FIGURE 13

THEORETICAL RELATIONSHIP BETWEEN MAJOR AND MINOR WEAR SCAR DIAMETERS

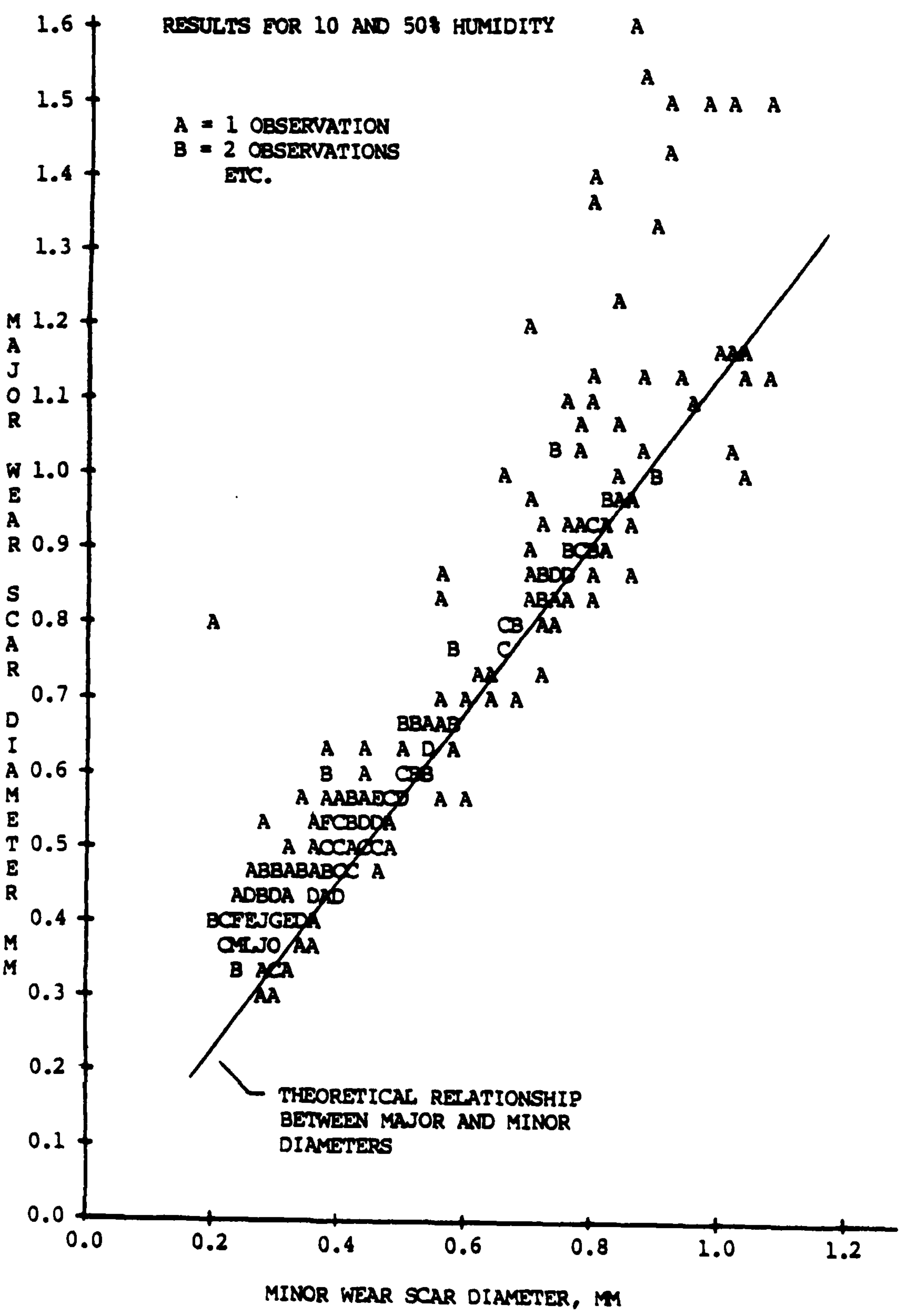


FIGURE 14

BOCLE ROUND ROBIN II

COMPARISON OF TRACK WIDTH TO MAJOR WEAR SCAR DIAMETER

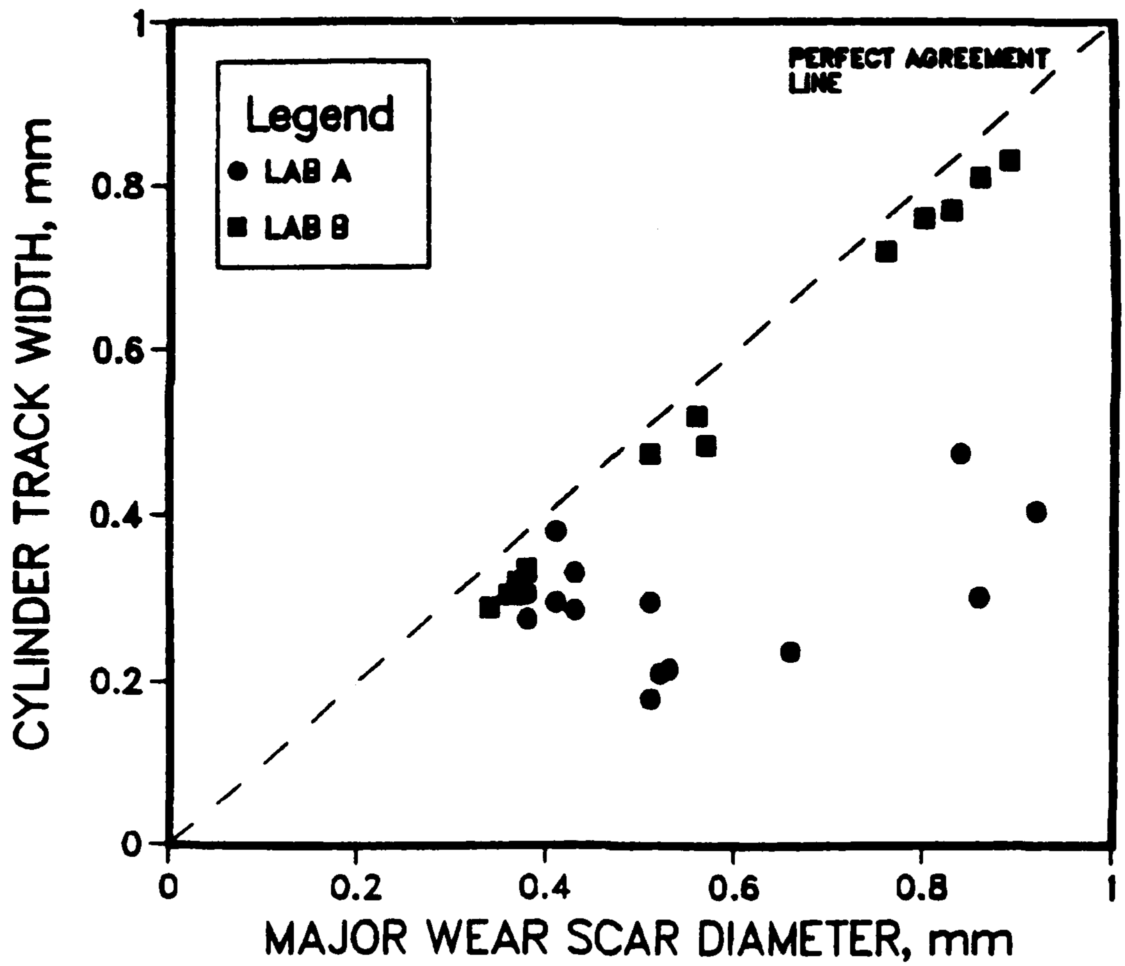


FIGURE 15

GEOMETRIC CRITERION FOR REVIEWING BOCLE RESULTS

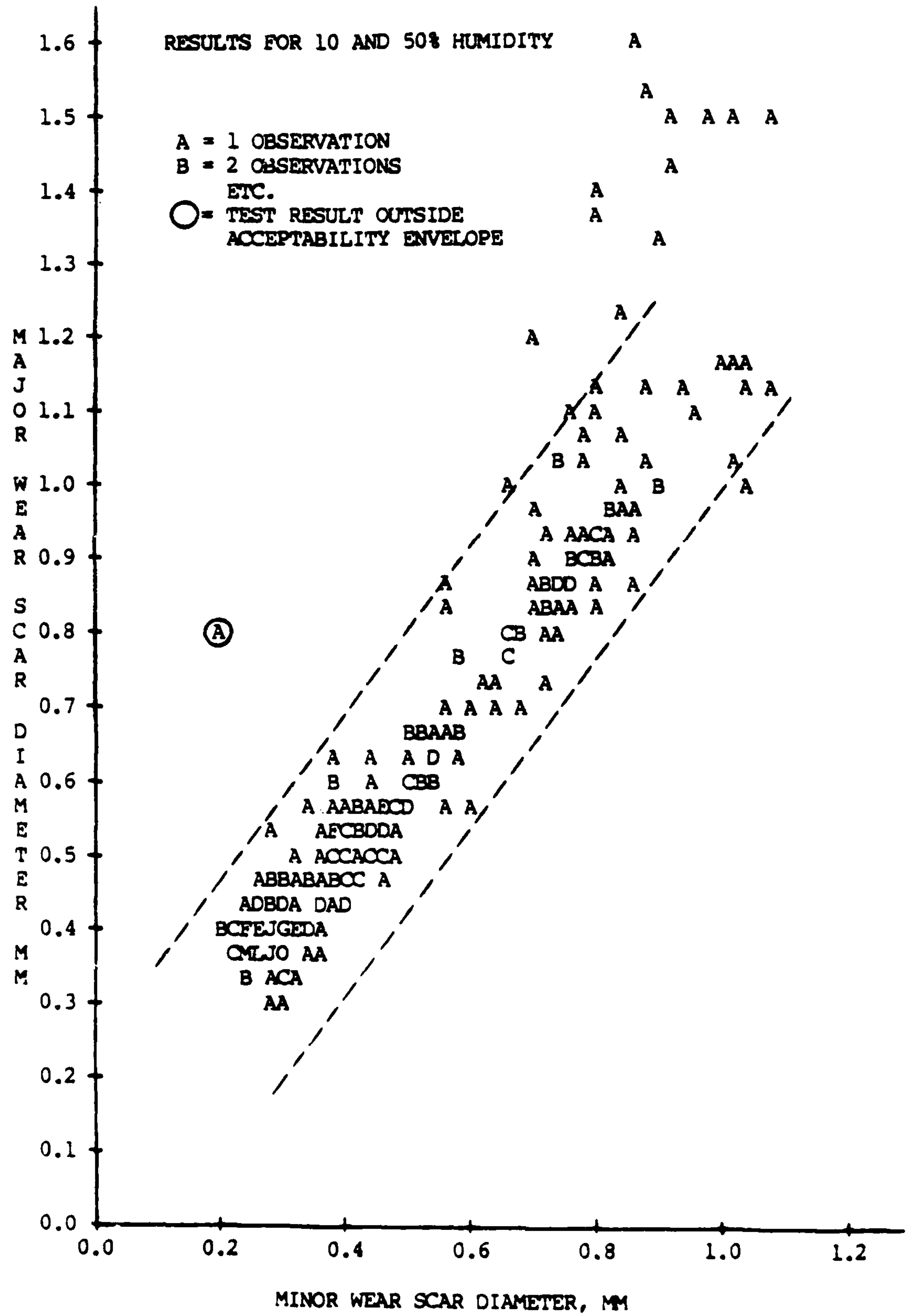


FIGURE 16

COMPARISON OF CYLINDER SUPPLIES

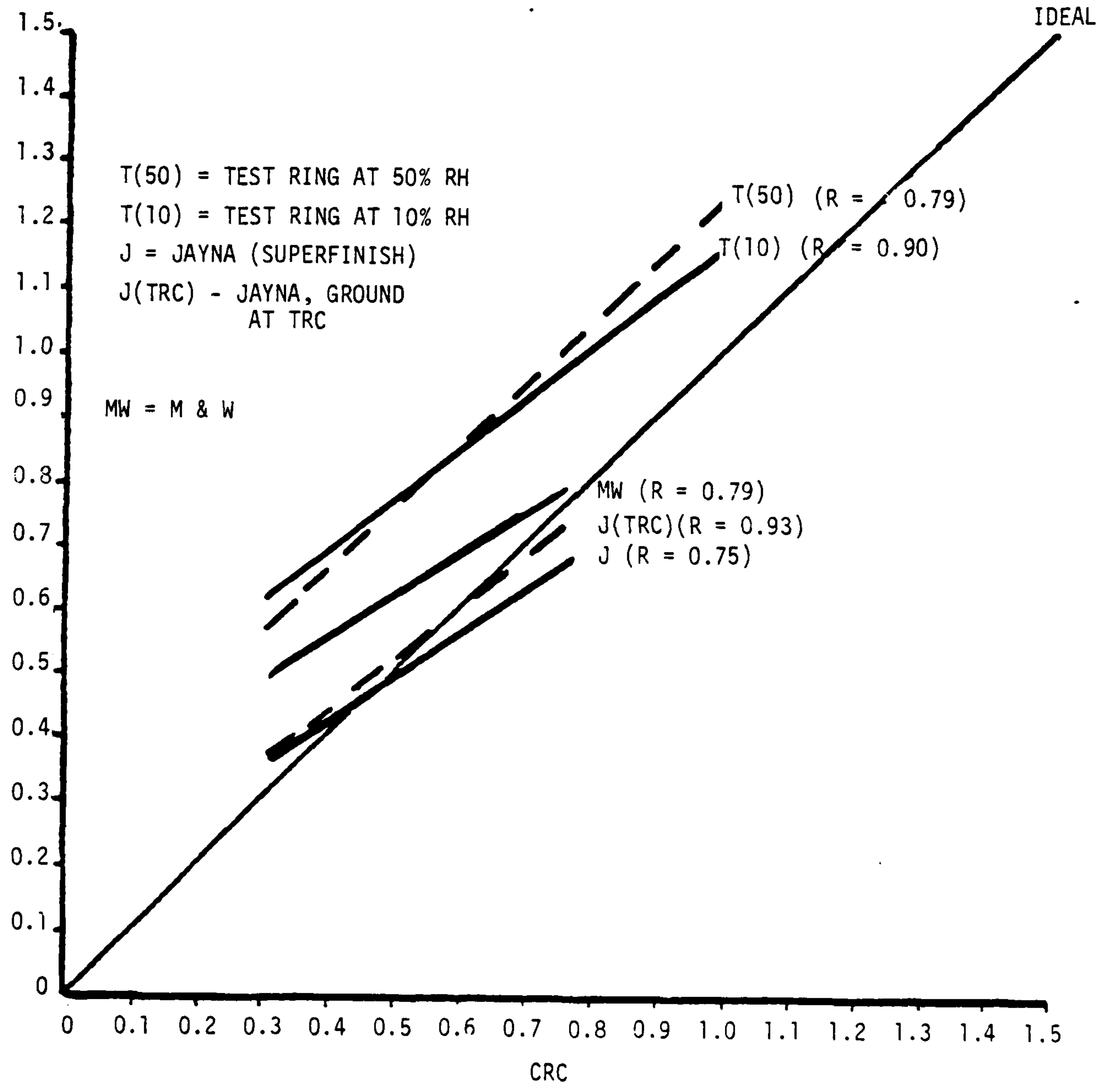


FIGURE 17

VARIATION IN BOCLE TEST RING LOTS

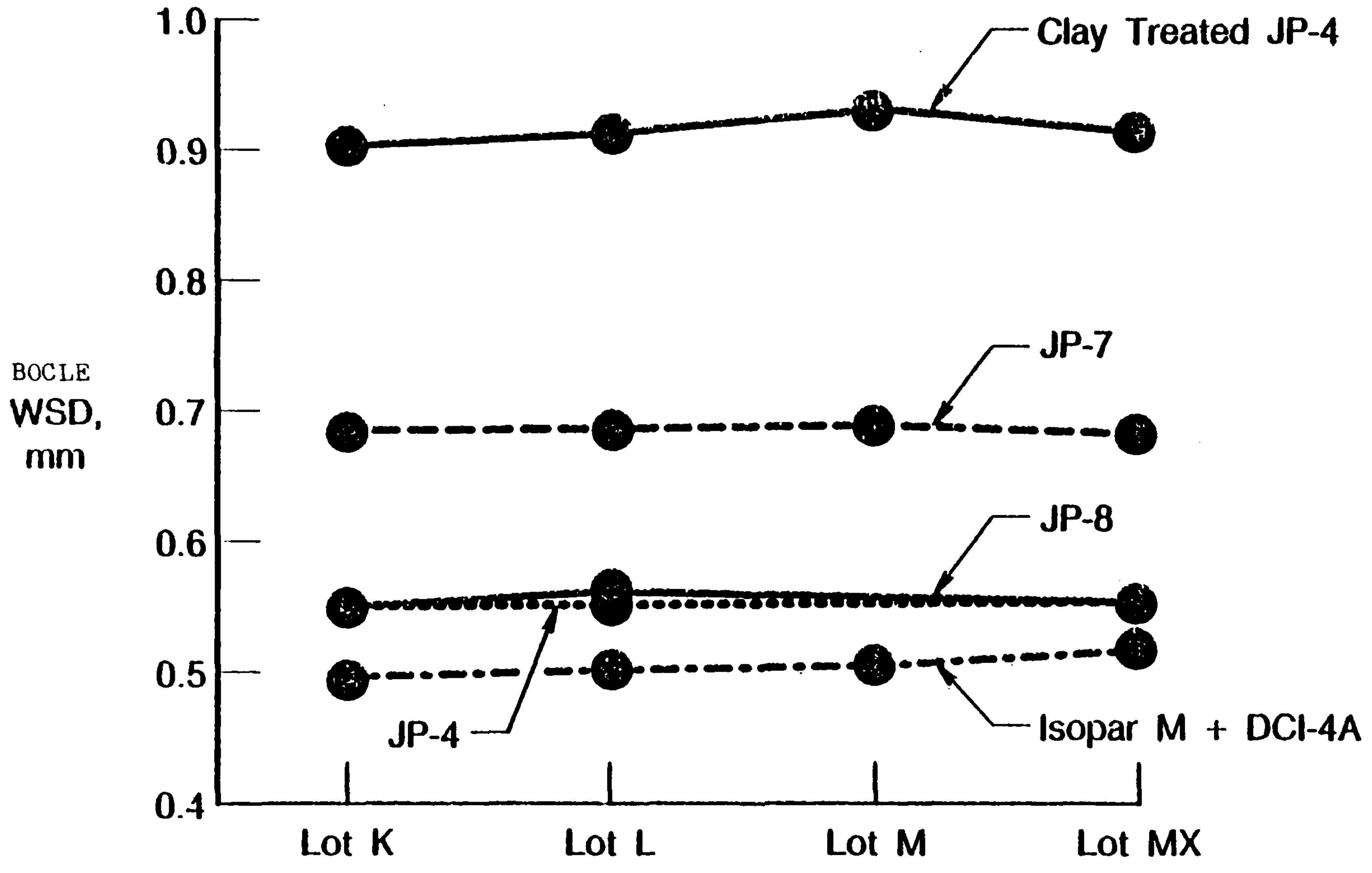


FIGURE 18

WEAR SCAR COMPARISON - TEST CYLINDER/TEST RING

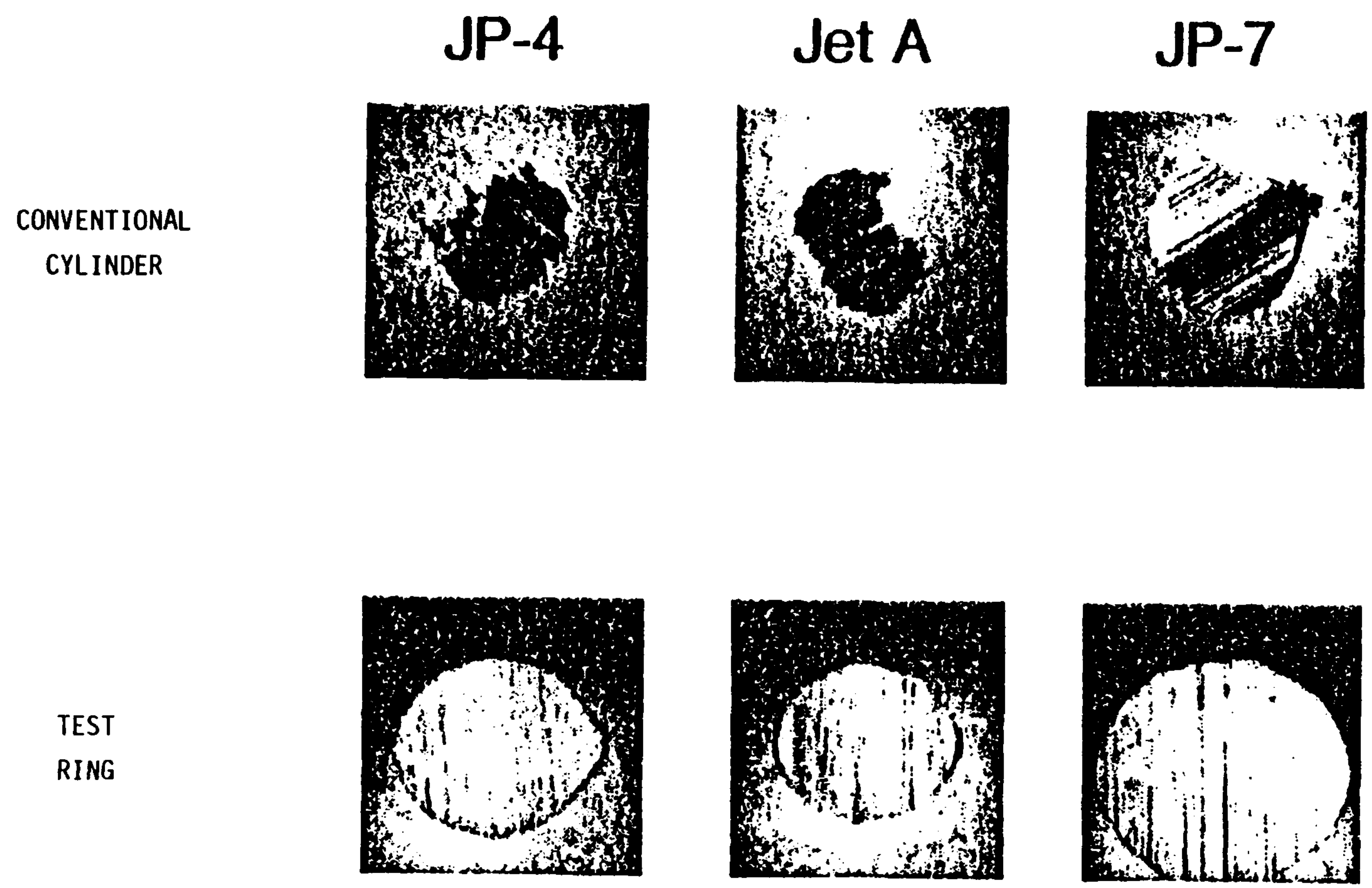
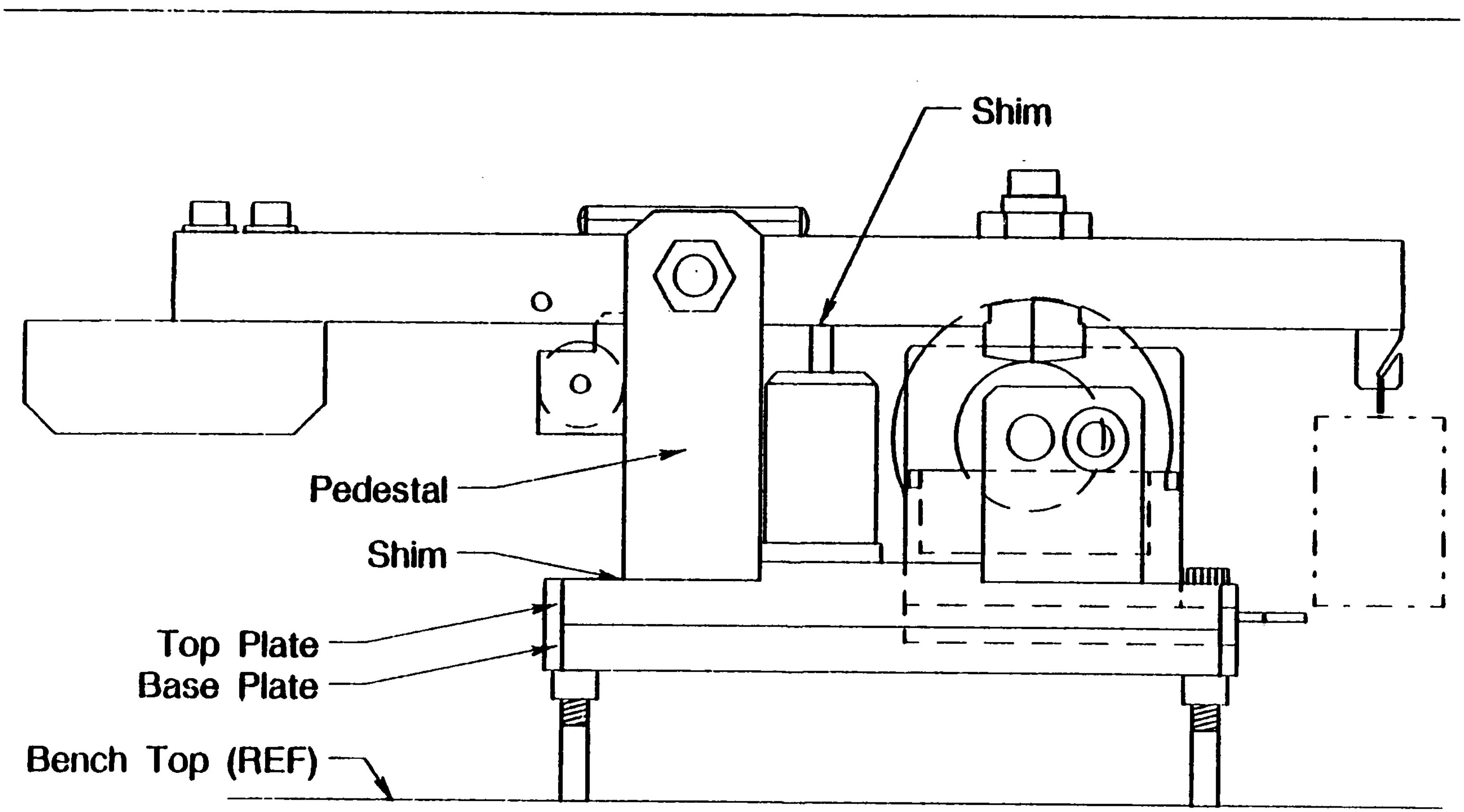


FIGURE 19

BOCLE MODIFICATION FOR TEST RING ADAPTION



APPENDIX A

TASK FORCE MEMBERSHIP
AND
PARTICIPATING LABORATORIES

CRC BALL-ON-CYLINDER LUBRICITY EVALUATOR TASK FORCE

Name	Affiliation
S. Bonifazi, Leader	Consultant
B. B. Baber	Southwest Research Institute
P. I. Barlow	Shell Research Ltd.
T. B. Biddle	Pratt & Whitney
R. J. Boness	Royal Military College
R. P. Bradley	Air Force Aero Propulsion Lab
H. G. Buschfort	InterAv Inc.
F. Carigiglitto	Sunstrand Aviation
J. C. Clerc	Chevron Research Company
J. P. Cuellar	Southwest Research Institute
G. Datschefski	Esso Research
L. A. Difford	Chandler Evans
W. G. Dukek	Consultant
* L. Grabel	Naval Air Propulsion Center
J. W. Hadley	Shell Research Ltd.
S. Humnicky	Allied Bendix
F. Hughes	Lucas Aerospace
R. A. Kamin	Naval Air Propulsion Center
J. H. Kimble	Allied Bendix
C. R. Martel	Air Force Aero Propulsion Lab
* A. R. Marsh	Pratt & Whitney
R. W. McCarthy	Woodward Governor
A. Mills	Ethyl Petroleum
F. P. Morse	Air Force SA-ALC
J. W. Muzatko	Chevron Research Company
C. S. Nau	Argo-Tech Corporation
R. Norrlander	Woodward Governor
J. D. Peluso	Naval Air Propulsion Center
H. W. Reynolds	Pratt & Whitney
J. Ricciardelli	Naval Air Propulsion Center
L. A. Sibert	Sunstrand Aviation
W. F. Taylor	Exxon Research & Engineering
R. D. Tharby	Petro-Canada Products
R. A. Vere	Esso Petroleum
P. E. Wolveridge	Shell Research Ltd.

* Deceased

PARTICIPATING LABORATORIES

Air Force
- Hill AFB
- Holloman AFB
- MacDill AFB
- Mountain Home AFB
- Mukilteo AFB
- Wright-Patterson AFB

Allied Bendix

British Petroleum

Chandler Evans

Chevron Research Co.

Esso Research

Ethyl Petroleum

Exxon Research & Engineering

Interav Inc.

German Ministry of Defense

Naval Air Propulsion Center

Petro-Canada

Pratt & Whitney (Connecticut)

Pratt & Whitney (Florida)

Rolls-Royce Ltd.

Shell Research Ltd.

Southwest Research Institute

Sundstrand AViation

Woodward Governor

APPENDIX B

BOCLE ROUND-ROBIN I TEST DETAILS

APPENDIX B

BOCLE ROUND-ROBIN I TEST DETAILS

1. Each laboratory participating in the round-robin will receive 13 test fluid samples from four sources: Navy (6), EXXON (4), Pratt & Whitney (2) and Chandler Evans (1).

2. Each fluid except isooctane and the 70:30 icooctane:toluene mixture is to be run in duplicate on the ball-on-cylinder machine under standard operating conditions. Isooctane and the 70:30 isooctane:toluene mixture are to be run using a 100g load because scuffing occurs at higher loads.

3. Each laboratory will run its tests in a different random order.

4. Tests should be run on consecutive days if possible and six tests should be run per day.

5. The cylinders used for the round-robin should be newly ground (or re-ground) and should not be used for any other testing. Each cylinder should be used for twelve tests. The first fluid evaluated on each new cylinder will be clay filtered Jet A (#1). This will serve as a control and a check on cylinder condition. If possible, the used test cylinders should be saved (not reground) until the test results have been fully analyzed. The balls used in the tests should also be marked for identification and retained.

6. Wear scar diameters should be measured using the "best fit ellipse" method. This method involves visually estimating where the outer edge of a smooth elliptical scar would fall if edge irregularities were not present.

7. The data sheet lists the wear scar diameters, test fluid temperatures and test cylinder hardness, surface finish and diameter. Only the wear scar diameters will be used to obtain estimates of repeatability and reproducibility; however, the other items may be useful in case there is any question about the acceptability of individual data points.

8. Test conditions for individual fluids have been chosen in an attempt to prevent scuffing from occurring. Scuffing is characterized by loud scraping noises during the test, the rubbing away of visible metallic particles, a very wide, jagged wear track on the cylinder and a wear scar similar to the one shown in photograph number 4 of Figure Q-6.

9. If a test run is known to be bad (e.g. visible contamination, broken air line, etc.), the data for this test run should not be reported. The test should instead be repeated, immediately if possible, using the same cylinder and the latter data reported.

APPENDIX C

BOCLE MINI-ROUND-ROBIN I TEST DETAILS

APPENDIX C

BOCLE MINI-ROUND-ROBIN I TEST DETAILS

1. The program involves four laboratories testing three samples each of four different fuels. Six of the samples will be tested on one day and the remaining six on the following day. After the two fuel testing days, the wear scar diameters (WSD) of the twelve balls will be remeasured on a third day and again on a fourth day.

A set of twelve fuels, eighteen balls and three data sheets will be provided to each participant. A test cylinder with a hardness of 28 Rockwell C will be provided to each participant. After receipt, the fuel samples should be stored at room temperature in the dark. The balls and cylinder should be cleaned and stored in a desiccator until used.

2. When the tests are performed, the cylinder should be aligned on the shaft so that the set screw is to the right when you are facing the front of the BOCLE. The first test should be started on the far left side of the cylinder and subsequent tests should progress from left to right on the cylinder.

3. A summary of the cleaning procedures, etching procedure and operating conditions follows:

3.1 CLEANING PROCEDURES

A. Cylinders - Initial Clean-Up

1. Wash with lab detergent and water. Use soft bristled brush. Avoid scratching polished surface with a metal brush handle.
2. Rinse thoroughly with distilled water.
3. Air dry.
4. Clean in soxhlet extractor using a 50/50 mixture of isopropyl alcohol and toluene or xylene. Reflux for 15 cycles or two hours, whichever is greater.
5. Dry in vacuum desiccator for 8 hours.
6. Store in desiccator.

B. Balls

1. Rinse with solvent to remove bulk of oil coating.
2. Follow steps 4-6 in A.

C. Reservoir

1. Disassemble reservoir for cleaning after each run.
2. Clean reservoir with solvent (acetone, alcohol, isooctane).
3. Blow dry with HC free air or dry with vacuum.

APPENDIX C (cont'd)

D. Cylinder on Spindle (between runs)

1. Remove as much test fluid as possible from cylinder using suction or by wiping with tissue.

2. Rinse with solvent.

3. Wipe with clean tissue or cloth.

4. Rinse and wipe again.

5. Dry with suction.

6. Make sure all test fluid and solvent are removed from areas around set screw and shaft/cylinder contact areas.

3.2 ETCHING PROCEDURE

Note: Balls must be cleaned per procedure in 3.1 before etching.

1. Press fit each ball into a suitable holder so that half of the ball surface is exposed (3/8" I.D. acid resistant tubing makes a good holder. The open end of the tubing should be plugged or sealed to prevent acid from getting in).

2. Fill a beaker with 50% HCl to a depth of about 3/4 inch (enough to cover the exposed part of the ball). Heat to boiling.

3. Place holder(s) ball side down into the boiling HCl solution (more than one ball can be etched at the same time). Continue boiling for two minutes. This should be long enough to make the polar and equatorial regions on the etched half of the ball visible to the naked eye. If they are not, reaction time should be increased.

4. Turn off heat and remove holder(s) from beaker. Immediately rinse balls in holders under cold running water to remove acid. After sufficient rinsing, remove balls from holders, rinse with acetone or alcohol and blow dry with compressed air. Store in desiccator. Prior to use, thoroughly rinse each ball with isooctane and wipe clean.

5. It is recommended that all test balls be etched at the same time prior to beginning the round-robin.

3.3 OPERATING CONDITIONS

A. Load: 1000g
B. Speed: 240 RPM
C. Duration: 30 minutes
D. Fuel Volume: 40 mL
E. Test Fluid Temperature: 77 ± 3°F (125 ± 1.5°C) temperature
F. Supply Air: 0.1 ppm hydrocarbons, 50 ppm water
G. *Purge Air: 10% Relative Humidity, 77 ± 3°F (25 ± 1.5°C) temperature
H. Pretreatment of Fuel in Reservoir:
   a. Length: 15 minutes
   b. Purge Air Flow Rate: 8 SCHF bubbling over and through test fluid
I. Purge Air Flow During Test: 8 SCFH bubbling over test fluid
J. Ball should be oriented so that wear scar falls in a non-polar/equitorial area.

APPENDIX D

BOCLE MINI-ROUND-ROBIN I INDIVIDUAL MEASUREMENTS

APPENDIX D

INDIVIDUAL MEASUREMENTS

FUEL - JP4

EXXON

SAMPLE		1			3			11	
MEASUREMENT	1	2	3	1	2	3	1	2	3
MAJOR DIAM.	.445	.440	.450	.510	.490	.485	.470	.470	.470
MINOR DIAM.	.390	.380	.380	.420	.420	.420	.410	.405	.405
WEAR-SCAR DIAM.	.4175	.4100	.4150	.4650	.4550	.4525	.4400	.4375	.4375
WEAR-SCAR VOL.	40.44	38.52	40.29	57.20	52.80	51.73	47.42	46.84	46.84

PRATT+WHITNEY

SAMPLE		2			8			10	
MEASUREMENT	1	2	3	1	2	3	1	2	3
MAJOR DIAM.	.410	.420	.410	.450	.450	.450	.430	.430	.430
MINOR DIAM.	.340	.340	.340	.360	.360	.360	.350	.350	.350
WEAR-SCAR DIAM.	.3750	.3800	.3750	.4050	.4050	.4050	.3900	.3900	.3900
WEAR-SCAR VOL.	29.93	31.40	29.93	38.17	38.17	38.17	33.88	33.88	33.88

SUNDSTRAND

SAMPLE		4			6			12	
MEASUREMENT	1	2	3	1	2	3	1	2	3
MAJOR DIAM.	.400	.400	.410	.390	.390	.390	.390	.400	.390
MINOR DIAM.	.340	.340	.340	.320	.320	.330	.330	.330	.340
WEAR-SCAR DIAM.	.3700	.3700	.3750	.3550	.3550	.3600	.3600	.3650	.3650
WEAR-SCAR VOL.	28.48	28.48	29.93	25.48	25.48	26.28	26.28	27.65	27.08

NAPC

SAMPLE		5			7			9	
MEASUREMENT	1	2	3	1	2	3	1	2	3
MAJOR DIAM.	.440	.440	.440	.450	.450	.450	.390	.390	.390
MINOR DIAM.	.370	.370	.370	.390	.390	.390	.310	.310	.310
WEAR-SCAR DIAM.	.4050	.4050	.4050	.4200	.4200	.4200	.3500	.3500	.3500
WEAR-SCAR VOL.	37.51	37.51	37.51	41.35	41.35	41.35	24.69	24.69	24.69

DIMENSIONS

MAJOR DIAMETER - mm
MINOR DIAMETER - mm
WEAR-SCAR DIAMETER - mm
WEAR-SCAR VOLUME - *10**(-6) cm**3

WEAR-SCAR DIAM.=(MAJOR DIAM.+MINOR DIAM.)/2
WEAR-SCAR VOL. =4/3*PI*((MAJOR DIAM.)/2)**2*((MINOR DIAM.)/2)

APPENDIX D

INDIVIDUAL MEASUREMENTS

FUEL - JP5

EXXON

SAMPLE		2			4			8	
MEASUREMENT	1	2	3	1	2	3	1	2	3
MAJOR DIAM.	.590	.590	.590	.590	.590	.590	.590	.600	.590
MINOR DIAM.	.525	.530	.530	.530	.520	.520	.530	.530	.540
WEAR-SCAR DIAM.	.5575	.5600	.5600	.5600	.5550	.5550	.5600	.5650	.565
WEAR-SCAR VOL.	95.69	96.60	96.60	96.60	94.78	94.78	96.60	99.90	98.4

PRATT+WHITNEY

SAMPLE		7			9			11	
MEASUREMENT	1	2	3	1	2	3	1	2	3
MAJOR DIAM.	.530	.530	.530	.590	.600	.590	.520	.520	.520
MINOR DIAM.	.450	.440	.450	.500	.510	.510	.440	.440	.450
WEAR-SCAR DIAM.	.4900	.4850	.4900	.5450	.5550	.5500	.4800	.4800	.485
WEAR-SCAR VOL.	66.19	64.71	66.19	91.13	96.13	92.96	62.30	62.30	63.7

SUNDSTRAND

SAMPLE		3			5			6	
MEASUREMENT	1	2	3	1	2	3	1	2	3
MAJOR DIAM.	.480	.480	.470	.530	.530	.530	.530	.530	.530
MINOR DIAM.	.400	.400	.420	.470	.480	.480	.480	.480	.480
WEAR-SCAR DIAM.	.4400	.4400	.4450	.5000	.5050	.5050	.5050	.5050	.505
WEAR-SCAR VOL.	48.25	48.25	48.58	69.13	70.60	70.60	70.60	70.60	70.6

NAPC

SAMPLE		1			10			12	
MEASUREMENT	1	2	3	1	2	3	1	2	3
MAJOR DIAM.	.500	.490	.510	.550	.550	.550	.470	.470	.470
MINOR DIAM.	.480	.440	.470	.480	.480	.480	.400	.410	.410
WEAR-SCAR DIAM.	.4900	.4650	.4900	.5150	.5150	.5150	.4350	.4400	.440
WEAR-SCAR VOL.	62.83	62.83	64.01	76.03	76.03	76.03	46.27	47.42	47.4

DIMENSIONS

MAJOR DIAMETER - mm
MINOR DIAMETER - mm
WEAR-SCAR DIAMETER - mm
WEAR-SCAR VOLUME - *10**(-6) cm**3

APPENDIX D

INDIVIDUAL MEASUREMENTS

FUEL - CFJP5

EXXON

SAMPLE		1			3			10	
MEASUREMENT	1	2	3	1	2	3	1	2	3
MAJOR DIAM.	.750	.740	.720	.760	.760	.760	.720	.720	.720
MINOR DIAM.	.660	.660	.650	.675	.670	.670	.590	.630	.630
WEAR-SCAR DIAM.	.7050	.7000	.6850	.7175	.7175	.7150	.6550	.6750	.6750
WEAR-SCAR VOL.	194.39	189.24	176.43	204.14	202.63	202.63	160.15	171.00	171.00

PRATT+WHITNEY

SAMPLE		2			6			7	
MEASUREMENT	1	2	3	1	2	3	1	2	3
MAJOR DIAM.	.580	.580	.580	.650	.650	.650	.540	.540	.540
MINOR DIAM.	.500	.500	.500	.550	.540	.540	.450	.460	.460
WEAR-SCAR DIAM.	.5400	.5400	.5400	.6000	.5950	.5950	.4950	.5000	.5000
WEAR-SCAR VOL.	88.07	88.07	88.07	121.67	119.46	119.46	68.71	70.23	70.21

SUNDSTRAND

SAMPLE		4			8			12	
MEASUREMENT	1	2	3	1	2	3	1	2	3
MAJOR DIAM.	.650	.660	.650	.740	.730	.730	.640	.640	.640
MINOR DIAM.	.570	.570	.580	.650	.640	.650	.570	.570	.550
WEAR-SCAR DIAM.	.6100	.6150	.6150	.6950	.6850	.6900	.6050	.6050	.5950
WEAR-SCAR VOL.	126.10	130.01	128.31	186.37	178.58	181.37	122.25	122.25	117.96

NAPC

SAMPLE		5			9			11	
MEASUREMENT	1	2	3	1	2	3	1	2	3
MAJOR DIAM.	.610	.610	.610	.640	.640	.640	.690	.700	.700
MINOR DIAM.	.530	.530	.530	.570	.570	.570	.630	.630	.630
WEAR-SCAR DIAM.	.5700	.5700	.5700	.6050	.6050	.6050	.6600	.6650	.6650
WEAR-SCAR VOL.	103.26	103.26	103.26	122.25	122.25	122.25	157.05	161.63	161.63

DIMENSIONS

MAJOR DIAMETER - mm
MINOR DIAMETER - mm
WEAR-SCAR DIAMETER - mm
WEAR-SCAR VOLUME - *10**(-6) cm**3

APPENDIX D

INDIVIDUAL MEASUREMENTS

FUEL - HARPOON

EXXON

SAMPLE		2			7			8	
MEASUREMENT	1	2	3	1	2	3	1	2	3
MAJOR DIAM.	.990	.990	.990	.940	.925	.930	.960	.960	.950
MINOR DIAM.	.885	.880	.880	.885	.860	.860	.865	.860	.860
WEAR-SCAR DIAM.	.9375	.9350	.9350	.9125	.8925	.8950	.9125	.9100	.9050
WEAR-SCAR VOL.	451.16	451.60	451.60	409.45	385.28	389.46	417.40	414.99	406.39

PRATT+WHITNEY

SAMPLE		3			5			11	
MEASUREMENT	1	2	3	1	2	3	1	2	3
MAJOR DIAM.	.830	.840	.840	.830	.830	.830	.840	.830	.830
MINOR DIAM.	.750	.750	.750	.720	.730	.720	.730	.730	.730
WEAR-SCAR DIAM.	.7900	.7950	.7950	.7750	.7800	.7750	.7850	.7800	.7800
WEAR-SCAR VO.	270.53	277.09	277.09	259.71	263.32	259.71	269.70	263.32	263.32

SUNDSTRAND

SAMPLE		4			9			12	
MEASUREMENT	1	2	3	1	2	3	1	2	3
MAJOR DIAM.	.840	.830	.850	.850	.840	.850	.860	.850	.850
MINOR DIAM.	.740	.750	.750	.760	.750	.760	.750	.760	.760
WEAR-SCAR DIAM.	.7900	.7900	.8000	.8050	.7950	.8050	.8050	.8050	.8050
WEAR-SCAR VOL.	273.39	270.53	283.73	287.51	277.09	287.51	290.44	287.51	287.51

NAPC

SAMPLE		1			6			10	
MEASUREMENT	1	2	3	1	2	3	1	2	3
MAJOR DIAM.	.860	.860	.860	.840	.840	.840	.810	.810	.820
MINOR DIAM.	.770	.770	.770	.730	.730	.740	.730	.730	.730
WEAR-SCAR DIAM.	.8150	.8150	.8150	.7850	.7850	.7900	.7700	.7700	.7750
WEAR-SCAR VOL	298.19	298.19	298.19	269.70	269.70	273.39	250.78	250.78	257.01

DIMENSIONS

MAJOR DIAMETER - mm
MINOR DIAMETER - mm
WEAR-SCAR DIAMETER - mm
WEAR-SCAR VOLUME - *10**(-6) cm**3

APPENDIX E

BOCLE MINI-ROUND-ROBIN I

COMPONENTS OF VARIANCE ESTIMATES

APPENDIX E

BOCLE MINI-ROUND-ROBIN I

COMPONENTS OF VARIANCE ESTIMATES
FULLY NESTED ANOVA MODEL

WEAR-SCAR DIAMETER VARIANCES mm**2

THREE LABORATORIES*

FUEL SOURCE OF VARIABILITY	DF	JP4	%	JP5	%	CFJP5	%	HARPOON	%
BETWEEN LABS	2	.0068	11.2	.0109	9.2	.1424	38.0	.0048	23.4
BETWEEN FUEL SAMPLES WITHIN LABS	6	.0537	88.2	.1042	88.2	.2317	61.8	.0145	70.7
BETWEEN MEASUREMENTS WITHIN FUEL SAMPLES	18	.0004	0.7	.0031	2.6	.0010	0.3	.0012	5.9
TOTAL VARIANCE		.0609		.1182		.3751		.0205	

FOUR LABORATORIES

FUEL SOURCE OF VARIABILITY	DF	JP4	%	JP5	%	CFJP5	%	HARPOON	%
BETWEEN LABS	3	.0737	58.3	.1036	49.2	.3142	62.3	.3768	93.8
BETWEEN FUEL SAMPLES WITHIN LABS	8	.0519	41.1	.1045	49.6	.1874	37.2	.0228	5.7
BETWEEN MEASUREMENTS WITHIN FUEL SAMPLES	24	.0007	0.6	.0024	1.1	.0028	0.6	.0020	0.5
TOTAL VARIANCE		.1263		.2105		.5044		.4016	

*No EXXON data.

APPENDIX F

BOCLE MINI-ROUND-ROBIN I

SAMPLE AVERAGES AND RANGES - THREE LABORATORY GROUP

APPENDIX F

BOCLE MINI ROUND-ROBIN I

WEAR-SCAR DIAMETER mm

THREE LABORATORIES*

	SAMPLE 1 $\overline{X}$	SAMPLE 1 R	SAMPLE 2 $\overline{X}$	SAMPLE 2 R	SAMPLE 3 $\overline{X}$	SAMPLE 3 R	LAB $\overline{X}$	LAB SD	FUEL $\overline{X}$	FUEL SD	d
FUEL - JP4											
PRATT-WHITNEY	.377	.005	.405	.000	.390	.000	.391	.012			.009
SUNDSTRAND	.372	.005	.357	.005	.363	.005	.364	.007			-.018
NAPC	.405	.000	.420	.000	.350	.000	.392	.032			.010
									.382	.020	
FUEL - JP5											
PRATT-WHITNEY	.483	.005	.550	.010	.482	.005	.507	.033			.018
SUNDSTRAND	.442	.005	.503	.005	.505	.000	.483	.031			-.006
NAPC	.482	.025	.515	.000	.438	.050	.478	.034			-.011
									.489	.033	
FUEL - CFJP5											
PRATT-WHITNEY	.540	.000	.597	.005	.498	.005	.545	.043			-.053
SUNDSTRAND	.613	.005	.690	.010	.602	.010	.635	.042			.037
NAPC	.570	.000	.605	.000	.663	.050	.613	.041			.015
									.589	.042	
FUEL - HARPOON											
PRATT-WHITNEY	.793	.005	.777	.005	.782	.005	.784	.008			-.008
SUNDSTRAND	.793	.010	.802	.010	.805	.000	.800	.007			.008
NAPC	.815	.000	.787	.005	.772	.005	.791	.019			-.001
									.792	.013	

Sample $\overline{X}$ - Average of 3 measurements.
Sample R - Range of 3 measurements.
Lab $\overline{X}$ - Average of 9 measurements.
Lab SD - Standard deviation of 9 measurements; df=8.
Fuel $\overline{X}$ - Average of 27 measurements.
Fuel SD - Standard deviation of 27 measurements; df=26.
d - Deviation of Lab $\overline{X}$ from Fuel $\overline{X}$; ($\overline{X}$(L)-$\overline{X}$(F)).

*No EXXON data.

APPENDIX 6

BOCLE MINI-ROUND-ROBIN I

SAMPLE AVERAGES AND RANGES - FOUR LABORATORY GROUP

APPENDIX G

BOCLE MINI ROUND-ROBIN I

WEAR-SCAR DIAMETER mm

FOUR LABORATORIES

	SAMPLE 1		SAMPLE 2		SAMPLE 3		LAB		FUEL		
	$\bar{X}$	R	$\bar{X}$	R	$\bar{X}$	R	$\bar{X}$	SD	$\bar{X}$	SD	d
FUEL - JP4											
EXXON	.414	.008	.458	.013	.438	.003	.437	.019			.041
PRATT-WHITNEY	.377	.005	.405	.000	.390	.000	.391	.012			-.005
SUNDSTRAND	.372	.005	.357	.005	.363	.005	.364	.007			-.032
NAPC	.405	.000	.420	.000	.350	.000	.392	.032			-.040
									.396	.020	
FUEL - JP5											
EXXON	.559	.003	.557	.005	.563	.005	.560	.004			.053
PRATT-WHITNEY	.483	.005	.550	.010	.482	.005	.507	.033			.000
SUNDSTRAND	.442	.005	.503	.005	.505	.000	.483	.031			-.024
NAPC	.482	.025	.515	.000	.438	.050	.478	.034			-.029
									.507	.028	
FUEL - CFJP5											
EXXON	.697	.020	.716	.003	.668	.020	.693	.022			.072
PRATT-WHITNEY	.540	.000	.597	.005	.498	.005	.545	.043			-.077
SUNDSTRAND	.613	.005	.690	.010	.602	.010	.635	.042			.013
NAPC	.570	.000	.605	.000	.663	.050	.613	.041			-.009
									.622	.038	
FUEL - HARPOON											
EXXON	.936	.003	.900	.020	.909	.008	.915	.017			.093
PRATT-WHITNEY	.793	.005	.777	.005	.782	.005	.784	.008			-.039
SUNDSTRAND	.793	.010	.802	.010	.805	.000	.800	.007			-.023
NAPC	.815	.000	.787	.005	.772	.005	.791	.019			-.031
									.823	.014	

Sample $\bar{X}$ - Average of 3 measurements.
Sample R - Range of 3 measurements.
Lab $\bar{X}$ - Average of 9 measurements.
Lab SD - Standard deviation of 9 measurements; df=8.
Fuel $\bar{X}$ - Average of 36 measurements.
Fuel SD - Standard deviation of 36 measurements; df=35.
d - Deviation of Lab $\bar{X}$ from Fuel $\bar{X}$; $(\bar{X}(L)-\bar{X}(F))$.

APPENDIX H

BOCLE MINI-ROUND-ROBIN II TEST DETAILS

APPENDIX H

BOCLE MINI-ROUND-ROBIN II TEST DETAILS

Six laboratories will test the cylinders with two test fluids: Reference Fuel 1 is a petroleum-derived JP-4 and Reference Fuel 2 is a shale-derived JP-4.

The six laboratories participating in this program are: EXXON Research and Engineering Co., Sundstrand, Southwest Research Institute, U. S. Air Force, U. S. Navy and Pratt & Whitney - Florida.

In order to verify the efficiency of the cleaning technique for removing traces of film-forming additives present in Reference Fuel No. 1, the next track on a cylinder should be run on Reference Fuel No. 2. The technique of alternating fuels between additive and non-additive fluids is widely practiced in lubricity testing and indicates from experience when a second cleaning is needed. Testing should start with Reference Fuel No. 2 in order to establish a base line.

The detailed testing procedure is Draft 2 of the Standard Test Method for the BOCLE. The important items to note are the following:

Paragraph 7.3.5 Cleaning after test should be followed using an ultrasonic cleaning unit. If solvents other than trichlorotrifluoroethane are used, please note.

Paragraph 9.22 (Table 1) Use 50 mL ± 2 mL sample size to standardize evaporation losses.

Table 1 Supply Air: Use reconstituted air rather than "zero" hydrocarbon air.

APPENDIX I

BOCLE MINI-ROUND-ROBIN II TEST DATA

APPENDIX I

BOCLE MINI-ROUND-ROBIN II

SUMMARY OF INDIVIDUAL WSD RESULTS

(Ball Wear Scar (mm) with Cylinders of Varying Alloy/Surface)

Lab \ Cyl		Ref. Fuel 40	Ref. Fuel 40L	Ref. Fuel 44	Ref. Fuel 44L	Test Fuel 40	Test Fuel 40L	Test Fuel 44	Test Fuel 44L
PWA (Interav)	1	.825		.865		.445		.450	
		.785		.800		.450		.425	
	2	.815		.730		.415		.400	
		.860		.780		.440		--	
USAF (Interav)	1		.715		.72#		.275W		.30
			~~.735~~A		~~.685~~		.265		.305
	2		1.08		.78		.28		.32
			.635		.95		.30		#.29
Sundstrand (W-G)	1	~~.83~~	.74			.38	.35		
		.93#	.75			.40	.31		
	2	.85	.85			.43	.31		
		.83	.75			.45	.39		
ERE (W-G)	1			.655	.655			.350	.290
				.680	.665			.360	.295
	2			.635	.665			.345	.305
				.690	.675			.370	.2[illegible]
Navy (ERE)	1	.99#		-A		.31			.36
		--A		-A		.42			.29
	2	.82#		-A		.38			.33
		--A		-A		.36			.42
SWRI (ERE)	1		.665	.815			.31 R	.42	
			.58 R	.685			.345 R	.41	
	2		.735 R	.85			.36	.45	
			.76	.865			.33	.43	

( ) = BOC Type
= Outliers on Precision Analysis

\# = Chatter
A = Test Aborted
W = Cylinder Wobbled
R = Cylinder Rusted

APPENDIX J

BOCLE MINI-ROUND-ROBIN II TEST

PROBABILITY DISTRIBUTION OF REPEATABILITY & REPRODUCIBILITY

APPENDIX J

BOCLE MINI ROUND-ROBIN II

PROBABILITY DISTRIBUTION OF REPEATABILITY AND REPRODUCIBILITY VARIANCE 1

------------------------ FUEL = REFERENCE ------------------------

SURFACE	LAB	CYLINDER	REPLICAT
40	0.00000000	0.00000000	0.00192813
40L	0.00134961	0.00026719	0.00397500
44	0.00501523	0.00000000	0.00389115
44L	0.00786604	0.00108375	0.00652750

SURFACE	REPEAT_V	REPROD_V	REPEAT	REPROD
40	0.00192813	0.0019281	0.124198	0.124198
40L	0.00397500	0.0055918	0.178326	0.211505
44	0.00389115	0.0089064	0.176435	0.266929
44L	0.00652750	0.0154773	0.228517	0.351878

------------------------ FUEL = TEST ------------------------

SURFACE	LAB	CYLINDER	REPLICAT
40	0.00098047	0.00000000	0.00118646
40L	0.00096354	0.00007292	0.00066458
44	0.00162846	0.00000000	0.00035592
44L	0.00058529	0.00002526	0.00104844

SURFACE	REPEAT_V	REPROD_V	REPEAT	REPROD
40	0.00118646	0.00216693	0.0974253	0.131664
40L	0.00066458	0.00170104	0.0729153	0.116655
44	0.00035592	0.00198438	0.0533607	0.125996
44L	0.00104844	0.00165899	0.0915834	0.115204

APPENDIX K

BOCLE MINI-ROUND-ROBIN II TEST

AVERAGE WEAR SCAR RESULTS AND STANDARD DEVIATIONS OF REPEATABILITY

APPENDIX K

BOCLE MINI-ROUND-ROBIN II

BALL WEAR SCAR (mm) WITH CYLINDERS OF VARYING ALLOYS/SURFACES

------------------------- FUEL=REFERENCE -------------------------

SURFACE	TESTRIG	LAB	CYLINDER	AVE_WEAR	STD_WEAR
40	1	PWA	1	0.8050	0.028284
40	1	PWA	2	0.8375	0.031820
40	2	SUMP	1	0.8800	0.070711
40	2	SUMP	2	0.8400	0.014142
40	3	NAVY	2	0.8200	.
40L	1	USAF	1	0.7250	0.014142
40L	1	USAF	2	0.6350	.
40L	2	SUMP	1	0.7450	0.007071
40L	2	SUMP	2	0.8000	0.070711
40L	3	SWRI	1	0.6225	0.060104
40L	3	SWRI	2	0.7475	0.017678
44	1	PWA	1	0.8325	0.045962
44	1	PWA	2	0.7550	0.035355
44	2	ERE	1	0.6675	0.017678
44	2	ERE	2	0.6625	0.038891
44	3	SWRI	1	0.7500	0.091924
44	3	SWRI	2	0.8575	0.010607
44L	1	USAF	1	0.6850	.
44L	1	USAF	2	0.8650	0.120208
44L	2	ERE	1	0.6600	0.007071
44L	2	ERE	2	0.6700	0.007071

------------------------- FUEL=TEST -------------------------

SURFACE	TESTRIG	LAB	CYLINDER	AVE_WEAR	STD_WEAR
40	1	PWA	1	0.4475	0.0035355
40	1	PWA	2	0.4275	0.0176777
40	2	SUMP	1	0.3900	0.0141421
40	2	SUMP	2	0.4400	0.0141421
40	3	NAVY	1	0.3650	0.0777817
40	3	NAVY	2	0.3700	0.0141421
40L	1	USAF	1	0.2700	0.0070711
40L	1	USAF	2	0.2900	0.0141421
40L	2	SUMP	1	0.3300	0.0282843
40L	2	SUMP	2	0.3500	0.0565685
40L	3	SWRI	1	0.3275	0.0247487
40L	3	SWRI	2	0.3450	0.0212132
44	1	PWA	1	0.4375	0.0176777
44	1	PWA	2	0.4000	.
44	2	ERE	1	0.3550	0.0070711
44	2	ERE	2	0.3575	0.0176777
44	3	SWRI	1	0.4150	0.0070711
44	3	SWRI	2	0.4400	0.0141421
44L	1	USAF	1	0.3025	0.0035355
44L	1	USAF	2	0.3050	0.0212132
44L	2	ERE	1	0.2925	0.0035355
44L	2	ERE	2	0.3000	0.0070711
44L	3	NAVY	1	0.3250	0.0494975
44L	3	NAVY	2	0.3750	0.0636396

APPENDIX L

BOCLE ROUND-ROBIN II TEST DETAILS

APPENDIX L

BOCLE ROUND-ROBIN II TEST DETAILS

There is participation from eight laboratories with the EXXON/Woodward BOCLE units and ten with the InterAv units. Each laboratory tests eight fuels at the standard condition given in the Draft 5 of the test procedure. Two test cylinders and sufficient test balls are supplied along with the order of testing for each laboratory. The fuels are tested immediately upon receipt to minimize the potential for change in lubricity during storage, with all samples run consecutively according to the statistical specified order of testing at a minimum of five per day.

The cylinders are AMS 6444 alloy with a 4-9micron AA surface finish chosen as the best metallurgical condition for uniform consistency.

Several tests at 50% relative humidity allow comparison with the standard 10% relative humidity to determine which provides the best precision.

APPENDIX M

BOCLE ROUND-ROBIN II

INDIVIDUAL RESULTS FOR EXXON/WOODWARD APPARATUS

APPENDIX M

BOCLE ROUND-ROBIN II - INDIVIDUAL RESULTS FOR EXXON/WOODWARD APPARATUS

Sample POSF	Laboratory A Cylinder		A Track	Laboratory B Cylinder		B Track	Laboratory C Cylinder		C Track	Laboratory D Cylinder		D Track
1431	.33	.23	.23	.355	.233	.102	.38/.33	.28/.21	.25	.30	.22	.20
	.39	.33	.27	.358	.237	.102	.39/.35	.30/.20	.33	.28	.21	.20
0988	.34	.31	.27	.379	.230	.102	.43/.36	.31/.22	.30	.29	.16	.24
	.33	.27	.31	.365	.233	.127	.39/.35	.27/.21	.28	.32	.19	.24
0708	.39	.36	.24	.498	.420	.102	.49/.49	.48/.32	.35	.37	.30	.15
	.42	.39	.25	.447	.406	.102	.52/.46	.49/.31	.35	.35	.30	.16
1775	.79	.66	.36	1.361	.792	.659	.94/.94	.85/.85	.60	Scuff		
	.66	.57	.44	1.534	.863	.761	1.78/1.25	1.30/.85	1.70	Scuff		
2071	.40	.29	.36	.391	.234	.152	.41/.31	.33/.24	.30	.30	.23	.22
	.42	.31	.26	.396	.247	.152	.39/.33	.36/.22	.30	.30	.20	.22
0709	.37	.25	.24	.381	.269	.102	.40/.40	.37/.31	.23	.37	.29	.25
	.38	.30	.24	.437	.289	.102	.42/.37	.32/.23	.26	.38	.28	.20
0878	.45	.41	.25	.686	.564	.076	.72/.72	.63/.63	.48	.66	.57	.30
	.60	.51	.40	.752	.609	.076	.85/.71	.71/.65	.63	.44	.37	.10
0847	.76	.59	.35	.894	.752	.254	.86/.86	1.00/.73	.75	Scuff		
	.81	.68	.30	.914	.782	.254	1.15/.95	1.25/.80	.90	Scuff		
2071(10)	.41	.31	.36				.43/.35	.37/.21	.26	.33	.22	.20
2071(50)	.66	.52	.52				.42/.38	.37/.26	.25	.35	.25	.30
	.52	.39	.40				.45/.31	.32/.24	.31	.34	.21	.25
0847(10)	.62	.58	.36				1.25/1.05	1.35/.80	1.10	.63	.53	.30
0847(50)	.80	.73	.64				1.20/.81	1.15/.95	.90	Scuff		
	.69	.67	.62				1.20/1.05	.90/1.20	.95	Scuff		
1431(10)				.376	.244	.102						
1431(50)				.386	.238	.152						
				.457	.305	.254						
1775(10)				1.016	.904	.203						
1775(50)				1.433	.924	.761						
				1.585	.833	.761						

APPENDIX M
(Continued)

BOCLE ROUND-ROBIN II - INDIVIDUAL RESULTS FOR EXXON/WOODWARD APPARATUS

Sample POSF	LABORATORY E* Cylinder		E* Track	F Cylinder		F Track	G** Cylinder		G** Track	H Cylinder		H Track
1431	.42	.28	.38	.38	.24	.30	.36	.25	.41	.39	.31	.30
	.41	.27	.38	.38	.24	.28	.38	.28	.38	.38	.30	.33
0988	.43	.37	.33	.37	.25	.26	.34	.24	.18	-	-	-
	.40	.37	.33	.38	.22	.28	.36	.25	.15	.39	.29	.30
0708	.56	.55	.18	.33	.30	.26	.84	.75	.33	.42	.39	.18
	.58	.51	.16	.36	.27	.24	.74	.62	.23	.53	.47	.13
1775	1.26	.85	1.00	.90	.75	.96C	.32	.23	.19T	.95	.83	.15
	1.39	.89	1.08	1.00	.65	1.02	.31	.25	.26T	.92	.83	.25
2071	.38	.36	.25	.40	.20	.28	-		.43	.38	.25	.30
	.37	.34	.28	.40	.20	.34	-		.43	.39	.26	.30
0709	.38	.38	.21	.37	.35	.30	.47	.38	.10	.39	.26	***
	.40	.30	.18	.37	.30	.24				.39	.26	***
0878	.65	.56	.10	.60	.50	.34	.84	.74	.18	.52	.42	-
	.75	.67	.13	.57	.50	.24	.97	.84	.20	.51	.39	-
0847	1.25	.85	.98	.83	.69	.26	.69	.53	.34T	.72	.72	.64
	1.20	.90	.97	.90	.70	.96C	.69	.56	.29T	.82	.72	.33
2071(10)	.42	.36	.34									
2071(50)	.41	.39	.32									
0847(10)	1.10	.72	.96									
0847(50)	1.07	.88	.83									
1431(10)				.38	.23	.30	.33	.25	.28			
1431(50)				.37	.22	.20	.38	.28	.43	.48	.39	.46
				.38	.28	.30	.32	.25	.20			
1775(10)				.70	.60	.30	.48	.45	.14T			
1775(50)				1.20	.70	1.38C	.69	.58	.19T	S	S	1.14
				1.10	.75	1.16C	.33	.31	.13T			

* Standard tests at 50-56% RH - extra tests at 64-64.5% RH
** Standard tests at 35-45% RH - extra tests at 40-47% RH
*** Cylinder tracks ran together

C = Loud Chatter
S = Wear Scar too large to read
T = Load 300 grams

A P P E N D I X   N

BOCLE ROUND-ROBIN II

SUPPLEMENTARY DATA FOR EXXON/WOODWARD APPARATUS

APPENDIX N

BOCLE ROUND-ROBIN II

SUPPLEMENTARY DATA FOR EXXON/WOODWARD APPARATUS

	BENDIX	WOODWARD GOVERNOR
BOCLE Modification		Woodward Governor
Compressed Air	AirProducts UP Grade	Double-Filtered Clay
Hygrometer	General Eastern 1100DP	Panametrics 2000
Bath Circulator		Arkay Corp CP-1000 Water Control Panel
Ultrasonic Bath		Cole-Farmer 8845-3
Wet Test Meter		
Load Mass, grams	500	500
Reference Standard		
Cleaning Method/Solvents		As Described
Initial Cylinder and Balls		Reflux[1] initial Ultrasonic before each test[2]
Reservoir/Utensils	Rinsed with Isooctane Final rinse with petroleum ether	Kim-Wipes and clay-filtered Isooctane
Cylinders		Between tests with Kim-Wipes and clay-filtered Isooctane
Drying Method/Conditions	Air Dry	As Described
Motor Shaft Coupling	Flexible	Rigid
Reservoir Removal Between Tests	Yes	Yes
Cylinder Removal Between Tests	No	No
Components Handling Method	Clean room gloves to handle cylinder & balls	Kim-Wipes & Cotton Gloves
Comments on Procedure, Materials, Etc.	Flowmeters: Dry air meter - F&P tube, etc.	[1]Reflex Solution: 50-50 Mixture of Isopropyl Alcohol and Isooctane. [2]Ultrasonic cleaner solution: 50-50 mixture of Isopropyl Alcohol and Clay-Filtered Isooctane.

APPENDIX N

BOCLE ROUND-ROBIN II

SUPPLEMENTARY DATA FOR EXXON/WOODWARD APPARATUS

	EXXON R&E	NAPC
BOCLE Modification	Woodward Governor	None
Compressed Air	House	None
Hygrometer	Phys-Chem Res.Corp Humeter	General Eastern 1200 APS
Bath Circulator		Neslab RTE 8
Ultrasonic Bath	Ace Scientific SC-101TH	Bransonic 220
Wet Test Meter	Fisher-Porter 10A1335	
Load Mass, grams	500	1000
Reference Standard		
Cleaning Method/Solvents	As Described	As Per Directions
Initial Cylinder and Balls	Reflux	
Reservoir/Utensils	Ultrasonic	
Cylinders	Ultrasonic	
Drying Method/Conditions	As Described	
Motor Shaft Coupling	Flexible	Rigid
Reservoir Removal Between Tests	Yes	No
Cylinder Removal Between Tests	Yes	Yes
Components Handling Method	As Described	Lint-Free Gloves Plastic Forceps
Comments on Procedure, Materials, Etc.	Method Followed	

APPENDIX N

BOCLE ROUND-ROBIN II

SUPPLEMENTARY DATA FOR EXXON/WOODWARD APPARATUS

	ESSO PETROLEUM	SUNDSTRAND
BOCLE Modification	None	Sundstrand
Compressed Air	Not Used	
Hygrometer	Not Used	
Bath Circulator	Not Used	
Ultrasonic Bath	Sonicor PTH-1546-2	
Wet Test Meter	Not Used	
Load Mass, grams	1000	500
Reference Standard		JP-4: 26 and 27mm on 1 cyl. 32.5mm on 2 cyl.
Cleaning Method/Solvents		
Initial Cylinder and Balls	Ultrasonic	Triple clay-filtered Isooctane Spray and wipe with Kleenex
Reservoir/Utensils	Ultrasonic	Triple clay-filtered Isooctane Spray and wipe with Kleenex
Cylinders	Ultrasonic	Triple clay-filtered Isooctane Spray and wipe with Kleenex
Drying Method/Conditions	Compressed Air	
Motor Shaft Coupling	Flexible	Rigid
Reservoir Removal Between Tests	Yes	Yes
Cylinder Removal Between Tests	Yes	Yes
Components Handling Method	Tweezers	Scott Tissues wet with Triple Filtered Isooctane covering fingers.
Comments on Procedure, Materials, Etc.	Test relative humidity ranged from 50-64.5%	

APPENDIX N

BOCLE ROUND-ROBIN II

SUPPLEMENTARY DATA FOR EXXON/WOODWARD

	LUCAS	CECO
BOCLE Modification	Exxon	Exxon
Compressed Air	Not Applicable	UPC Air Products A01-P-00514 Size A
Hygrometer	Not Applicable	General Eastern 1100 DP
Bath Circulator	Not Applicable	
Ultrasonic Bath	Dewes	
Wet Test Meter	Not Applicable	
Load Mass, grams	500, 150	1000
Reference Standard		
Cleaning Method/Solvents	As Per Instructions	Reflux
Initial Cylinder and Balls	Ultrasonic	Heptane, Alconox Scrub, water rinse, nitrogen dry, 50/50 Isopropanol & Xylene Reflux (15 times), vacuum dessiccator
Reservoir/Utensils		Acetone rinse, nitrogen dry (3 times)
Cylinders		Nitrogen UPC Air Products A01-T-3901A-Size A
Drying Method/Conditions		
Motor Shaft Coupling	Flexible	Flexible
Reservoir Removal Between Tests	Yes	Yes
Cylinder Removal Between Tests	Yes	Yes
Components Handling Method	Tangs, disposable gloves	Tangs
Comments on Procedure, Materials, Etc.	Central hole slightly oversized and adjusted. Steel ball corrosion observed after cleaning. No temperature or humidity control.	All tests (original) for cylinder 1 were run without temperature control. Temp. averaged. Tests for cylinder 2 (run on 1 since 2 was unsatisfactory) were temperature controlled. Rust found on both cylinders after cleaning.

A P P E N D I X   O

BOCLE ROUND-ROBIN II

INDIVIDUAL RESULTS FOR INTERAV APPARATUS

APPENDIX O

BOCLE ROUND-ROBIN II INDIVIDUAL RESULTS FOR INTERAV APPARATUS

	LABORATORY									
	A		B		C		D		E	
Sample POSF	Cylinder	Track	Cylinder	Track	Cylinder	Track	Cylinder	Track	Cylinder	Track
1431	.42 .39	.30	.37 .25	.30	.41 .23	.24	.36 .30	.24	.37 .29	.36
	.41 .30	.30	.36 .25	.37	.39 .24	.28	.36 .29	.25	.37 .29	.31
0988	.37 .28	.28	.34 .24	.32	.37 .26	.33	.33 .29	.32	.38 .34	.26
	.38 .28	.28	.37 .27	.30	.39 .27	.32	.35 .30	.30	.39 .33	.28
0708	.53 .46	.15	.51 .44	.24	.46 .42	.22	.52 .45	.26	.50 .48	.21
	.51 .46	.15	.57 .40	.24	.48 .41	.30	.54 .43	.36	.52 .47	.22
1775	.56 .46	.23	.76 .68	.18	.92 .78	.42	.85 .55	.17	1.03 .88C	1.05C
	.58 .49	.23	.89 .79	.57	.88 .76	.45	.84 .55	.35	.95 .85	.33N
2071	.43 .26	.30	.37 .27	.32	.48 .27	.30	.39 .31	.23	.40 .30	.37
	.42 .26	.30	.38 .28	.38	.45 .29	.28	.39 .31	.20	.39 .30	.41
0709	.53 .44	.30	.38 .29	.24	.45 .35	.33	.46 .40	.34	.50 .36	.30
	.48 .38	.30	.38 .29	.24	.42 .38	.32	.44 .29	.27	.47 .33	.27
0878	.71 .63	.20	.56 .48	.26	.62 .54	.24	.58 .50	.21	.60 .52	.15
	.73 .62	.10	.89 .77	.53	.61 .54	.12	.56 .48	.15	.60 .49	.15
0847	.54 .40	.20	.86 .76	.61	.84 .73	.75	.88 .70	.80	1.00 .89	.42G
	.68 .57	.20	.80 .72	.60	.81 .67	.50	.94 .71	.80	.93 .82	.75N
2071(10)	.38 .27	.30			.47 .25	.35			.40 .28	.31
2071(50)	.58 .41	.40			.47 .31	.40			.45 .37	.30
	.49 .37	.38			.45 .34	.39			.43 .35	.40
0847(10)	.55 .45	.33			.85 .72	.85			.94 .80	-
0847(50)	.62 .49	.25			.96 .69	.90			1.05 .78	.78
	.56 .45	.33			1.03 .73	.99			.84 .80	-
1431(10)			.37 .24	.30			.31 .29	.30		
1431(50)			.36 .26	.32			.34 .29	.16		
			.40 .30	.36			.40 .33	.37		
1775(10)			.83 .71	.34			.80 .70	.50		
1775(50)			1.15 .80	1.16			1.07 .77	.95		
			1.40 .80	1.40			1.03 .74	.93		

C=Loud chatter; G=Grinding; N=Excessive noise; L=Loud screech; S=Scuff

APPENDIX O
(Continued)
BOCLE ROUND-ROBIN II INDIVIDUAL RESULTS FOR INTERAV APPARATUS

	LABORATORY									
	F		G		H		I		J	
Sample POSF	Cylinder	Track	Cylinder	Track	Cylinder	Track	Cylinder	Track	Cylinder	Track
1431	.39 .28	.34	.41 .27	.38	.30 .22	.23	.38 .24	.29	.40 .25	.26
	.38 .29	.35	.38 .26	.28	.33 .25	.27	.38 .24	.30	.40 .25	.24
0988	.40 .28	.31	.43 .24	.28	.31 .21	.17	.41 .25	.29	.30 .28	.22
	.39 .28	.32	.43 .25	.33	.31 .22	.17	.43 .25	.30	.35 .22	.24
0708	.51 .45	.20	.51 .43	.22	.36 .30	.20	.55 .47	.17	.45 .40	.15
	.51 .44	.22	.53 .44	.18	.37 .28	.16	.55 .47	.17	.50 .45	.30
1775	.95 .82	.65	1.00 .83	-	.52 .43	.27	.91 .79	.27	.85 .60	.12
	.94 .80	.45	.88 .80	-	.44 .37	.30	1.16 1.04	1.31S	.85 .75	.46
2071	.41 .27	.34	.41 .23	.30	.32 .25	.23	.40 .22	.32	.35 .30	.31
	.41 .28	.32	.38 .24	.30	.30 .22	.22	.41 .21	.34	.38 .25	.28
0709	.42 .36	.38	.52 .40	.21	.31 .25	.18	.43 .30	.35	.46 .40	.32
	.43 .36	.32	.51 .38	.30	.32 .24	.18	.44 .35	.35	.44 .45	.45
0878	.62 .54	.12	.66 .56	.24	.55 .46	.17	.59 .50	.13	.55 .50	.24
	.60 .54	.20	.92 .79	.40	.49 .42	.16	.58 .50	.28	.58 .55	.31
0847	.86 .74	.60	.84 .75	.48	.62 .54	.25	1.50 .98	1.42S	.75 .68	.41
	1.06 .84	.95G	.86 .74	.30	.66 .56	.26	.85 .73	.49	.85 .75	.43
2071(10)					.32 .22	.25	.39 .22	.31		
2071(50)					.30 .21	.25	.50 .32	.41		
					.35 .22	.19	.45 .30	.40		
0847(10)					L		1.13 .88	1.02S		
					L					
0847(50)					.85 .57	.70	1.24 .84	1.17S		
							1.11 .81	1.12S		
1431(10)	.38 .29	.38	.43 .28	.36						
1431(50)	.40 .30	.35	.44 .30	.34						
	.38 .30	.32	.46 .28	.34						
1775(10)	.89 .79	.42G	.85 .74	-						
1775(50)	1.35 .90	1.25	Scuff 4.5 min.							
	1.51 .91	1.45G	Scuff 4 min.							

C=Loud chatter; G=Grinding; N=Excessive noise; L=Loud screech; S=Scuff

APPENDIX P

BOCLE ROUND-ROBIN II

SUPPLEMENTARY DATA FOR INTERAV APPARATUS

APPENDIX P

BOCLE ROUND-ROBIN II

SUPPLEMENTARY DATA FOR INTERAV APPARATUS

	SWRI	P&W
BOCLE Modification		
Compressed Air	Bottled Synthetic	Bottled
Hygrometer		
Bath Circulator		NesLab EX-100DD
Ultrasonic Bath		Sonicor SC-50TH
Wet Test Meter		
Load Mass, grams		1000
Reference Standard		Isopar M&DCI-4A, .44 and .46 on 2 cylinders
Cleaning Method/Solvents	Alternate Cleaning Method	
Initial Cylinder and Balls		Ultrasonic 50-50 Isopropyl alcohol & toluene
Reservoir/Utensils		Isooctane, blow dry, Acetone, blow dry
Cylinders		Isooctane, blow dry, Acetone, blow dry
Drying Method/Conditions		Bottled Air
Motor Shaft Coupling		Rigid
Reservoir Removal Between Tests		No
Cylinder Removal Between Tests		No
Components Handling Method		White Cotton Gloves
Comments on Procedure, Materials, Etc.		Impossible to ultrasonically clean reservoir after each run due to constant temperature bath lines attached to reservoir.

APPENDIX P

BOCLE ROUND-ROBIN II

SUPPLEMENTARY DATA FOR INTERAV APPARATUS

	NAPC	THORNTON	AF BASE B
BOCLE Modification			
Compressed Air		BOC standard	Yes
Hygrometer			
Bath Circulator	NesLab RTE 8	Grant FH15	
Ultrasonic Bath	Bransonic 220	Rapidclean 16	Sonicor
Wet Test Meter			
Load Mass, grams			1000
Reference Standard			No
Cleaning Method/Solvents	As per directions		
Initial Cylinder and Balls		Ultrasonic	Ultrasonic
Reservoir/Utensils		Ultrasonic	
Cylinders		Ultrasonic	
Drying Method/Conditions		Wiped with tissues, then blow dry	
Motor Shaft Coupling	Rigid	Rigid	Flexible
Reservoir Removal Between Tests	Yes	Yes	Yes
Cylinder Removal Between Tests	Yes	Yes, except when same fuel used	Yes
Components Handling Method	Lint-free Gloves, Plastic Forceps		
Comments on Procedure, Materials, Ftc.		Generally alternate method used. Reservoir, cover & cylinder ultrasonically cleaned when fuel changed.	

APPENDIX P

BOCLE ROUND-ROBIN II

SUPPLEMENTARY DATA FOR INTERAV APPARATUS

	AF BASE C	AF BASE D
BOCLE Modification		
Compressed Air	Base Air	Base
Hygrometer		
Bath Circulator		
Ultrasonic Bath	Sonicor	Sonicor
Wet Test Meter		
Load Mass, grams	1000	1000
Reference Standard		
Cleaning Method/Solvents		
Initial Cylinder and Balls	Ultrasonic	Ultrasonic
Reservoir/Utensils		
Cylinders		
Drying Method/Conditions		
Motor Shaft Coupling	Flexible	Flexible
Reservoir Removal Between Tests	Yes	Yes
Cylinder Removal Between Tests	Yes	Yes
Components Handling Method		
Comments on Procedure, Materials, Etc.	Constant removal & cleaning was very cumbersome & walking of cylinder from one assigned track to another was seen. Excessive handling also resulted in dropping the cylinder. We recommend that sonication of the cylinder, reservoir, etc., be compared to simple solvent rinsing & air drying. The procedure followed & materials & equipment used were those supplied or recommended by AFWAL/POSF except that purified "house air" is used as the air source.	

APPENDIX P

BOCLE ROUND-ROBIN II

SUPPLEMENTARY DATA FOR INTERAV APPARATUS

	AFWAL/POSF	EDWIN COOPER
BOCLE Modification		
Compressed Air		As specified - CRC supplied
Hygrometer		
Bath Circulator		
Ultrasonic Bath	Sonicor	
Wet Test Meter		In House
Load Mass, grams	1000	500
Reference Standard	70/30	
Cleaning Method/Solvents		
Initial Cylinder and Balls	Ultrasonic	Pet Ether - Ultrasonic
Reservoir/Utensils	X	Pet Ether
Cylinders	X	Pet Ether
Drying Method/Conditions		Blow Dry/Compressed Air
Motor Shaft Coupling	Flexible	Rigid
Reservoir Removal Between Tests	Yes	Yes
Cylinder Removal Between Tests	Yes	Yes
Components Handling Method		Polythene Gloves
Comments on Procedure, Materials, Etc.		Circulating water and air required heating. Alternate method (7.3.1A) used for cleaning. Specimens not stored in desiccator but used immediately after drying. Non-traveling microscope used.

APPENDIX Q

BOCLE ROUND-ROBIN II

STANDARD TEST METHOD FOR MEASUREMENT OF LUBRICITY OF LIQUID HYDROCARBON FUELS BY THE BALL-ON-CYLINDER LUBRICITY EVALUATOR

STANDARD TEST METHOD FOR MEASUREMENT OF LUBRICITY OF LIQUID HYDROCARBON FUELS BY THE BALL-ON-CYLINDER LUBRICITY EVALUATOR[1] FOR SECOND ROUND ROBIN

1. Scope

1.1 This method assesses the boundary lubrication properties of aviation fuels and similar hydrocarbon liquids on rubbing steel surfaces.

1.2 This standard may involve hazardous materials, operations and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of whoever uses this standard to consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use. For specific precautions, see 7.3, 7.8, 7.9, and 7.10.

2. Applicable Documents

2.1 ASTM Standards

D329, Specification for Acetone[3]
D770, Specification for Isopropyl Alcohol[3]
D1016, Purity of Hydrocarbons from Freezing Points[2]
D4306, Practice for Sampling Aviation Fuel for Tests Affected by Trace Contamination[5]

2.2 Military Specifications

MIL-I-25017, Inhibitor, Corrosion, Fuel Soluble

2.3 Aerospace Material Specification

AMS 6444, Steel Bars, Forgings, and Tubing, Premium Aircraft-Quality, Consumable Electrode Vacuum Melted.

2.4 AISI Standards

AISI E-52100 Chromium Alloy Steel

2.5 American National Standards Institute Specification

ANSI B3.12, Metal Balls

2.6 Other

ASTM RR: D2-1007, Manual on Determining Precision Data for ASTM Methods on Petroleum Products and Lubricants.

[1] Current edition distributed ______________
[2] Annual Book of ASTM Standards, Vol. 05.01
[3] Annual Book of ASTM Standards, Vol. 06.03
[4] Annual Book of ASTM Standards, Vol. 05.C2
[5] Annual Book of ASTM Standards, Vol. 05.03

3. Terminology

3.1 Description of Terms Specific to This Standard.

3.1.1 Lubricity - A property measurement of the fluid, in millimeters, of the wear produced on a stationary ball from contact with the fluid wetted rotating cylinder operating under closely controlled conditions.

4. Summary of Method

4.1 The fluid under test is placed in a test reservoir in which atmosphere air is maintained at 10% relative humidity. A non-rotating steel ball is held in a vertically mounted chuck and forced against an axially mounted steel cylinder with an applied load. The test cylinder is rotated at a fixed speed and receives a momentary exposure to the test fluid upon each revolution. The wear scar generated on the test ball is a measure of the fluid lubricating properties.

5. Significance and Use

5.1 In recent years, high grades of crude oil have become increasingly harder to obtain. Manufacturers of aircraft turbine fuels have been forced to use lower grade petroleum and synthetic crude oils as feedstock material. These low quality feedstocks have necessitated the use of the hydrotreating refinery process which removes or reduces the lubricity enhancing molecules that naturally occur in crudes. These polar constituents provide the boundary layer lubrication necessary for engine fuel system components.

5.2 Wear due to excessive friction resulting in shortened life of engine components such as fuel pumps and fuel controls have sometimes been ascribed to lack of lubricity in an aviation fuel.

5.3 The relationship of test results to aviation fuel system component distress due to wear has been demonstrated on occasions where boundary lubrication is a factor in the operation of the component.

5.4 The wear scar generated in the BOCLE test is sensitive to contamination of the fluids and test materials, the presence of oxygen and water in the atmosphere, and the temperature of the test.

5.5 This test method was developed by the Coordinating Research Council and is a part of their report.

6. Apparatus

6.1 Ball-on-Cylinder Lubricity Evaluator (BOCLE), illustrated in Figures 1 and 2 [*] of this appendix.

6.2 Constant Temperature Bath-Circulator, capable of maintaining the fluid sample at 25 ± 1.0°C when circulating water through the base of the sample reservoir.

[*] BOCLE units made by InterAv, Inc., P.O. Box 16714, San Antonio, TX 78216 have been found satisfactory.

6.3 Microscope, capable of 100X magnification and traverse with a recticle in graduations of 0.1mm and incremented in divisions of 0.01mm.[7]

6.4 Cleaning Bath, Ultrasonic seamless stainless steel tank with a capacity of 1.9 L (1/2 gal) and a cleaning power of 40W.[8]

7. Reagents and Materials

7.1 Test Cylinder, 100% spheroidized annealed bar stock, consumable vacuum melted AMS 6444 steel cylinder: 44.45mm (1 3/4 in.) outside diameter x 7.93mm (5/16 in.) inside diameter x 19.05mm (3/4 in.) wide with a 0.0127mm (0.0005 in.) cylindricity. The hardness shall be 226-237 BHN (20-22 R_C). The cylinder shall be ground to a 0.10-0.23μmAA (4-9μin.AA) surface finish (Figure Q-3)[9]

7.2 Test Ball, chrome alloy steel, made from AISI standard steel No. E-52100, with a diameter of 12.7 mm (0.5 in.), Grade 25 EP (Extra Polish). The balls are described in ANSI Specifications B3.12, for Metal Balls. The Extra-Polish finish is not described in that specification. The Rockwell C hardness shall be 64 to 66, a closer limit than is found in the ANSI requirement.[10]

7.3 Compressed Air (Caution - Compressed gas under high pressure. See Annex A.1.1), containing less than 0.1 ppm hydrocarbons and 50 ppm water.

7.4 Desiccator, containing a non-indicating drying agent, capable to store test cylinders, balls, and hardware.

7.5 Gloves, clean, lint-free, cotton, disposable.

7.6 Wiper, wiping tissue, light duty, lint free, disposable.[11]

7.7 Detergent, heavy duty water soluble laboratory type.[12]

7.8 Isooctane (Danger - Extremely flammable. Harmful if inhaled. Vapors may cause flash fire. See Annex A.1.2), conforming to ASTM D1016, 95% purity minimum.

[7] The Unitron inverted metallurgical microscope monocular Model Series MEC or binocular Model Series BMEC from Unitron Instruments, Inc., 175 Express Street, Plainview, NY 11803 have been found satisfactory.

[8] Ultrasonic cleaner with timer from Sonicor Instrument Corp., 1365 Marconi Boulevard, Copiaque, NY 11726 or VWR Scientific, P.O. Box 7900, San Francisco, CA 94120, have been found satisfactory.

[9] Test cylinders from Jayna Enterprises, Inc., 886 Center Drive, Vandalia, OH 45377 have been found satisfactory.

[10] Test balls from Falex Corp., 2055 Comprehensive Drive, Aurora, IL 60505 have been found satisfactory.

[11] Kimwipe wipers made by Kimberly-Clark Corp., Roswell, Georgia 30076 and Micro-Wipes #5310 made by Scott Paper Co., Philadelphia, PA have been found satisfactory.

[12] Alconox made by Alconox Inc., New York, NY 10003 have been found satisfactory.

7.9 Isopropyl Alcohol (Warning - Flammable. See Annex A.1.3), conforming to ASTM D770, refined 99%.

7.10 Acetone (Danger - Extremely flammable. Vapors may cause flash fire. See Annex A.1.4), conforming to ASTM D329.

7.11 Standard Reference Fluid, a mixture to contain the specified 29 ppm fuel soluble corrosion inhibitor/lubricity improver[13], conforming to MIL-I-25017 in the specified narrow-cut isoparaffinic solvent.[14] Store in borosilicate glass with an aluminum foil lined insert cap. Store in a dark area.

8. Preparation of Apparatus

8.1 Test Material Identification

8.1.1 Test cylinders shall be identified when new to reference batches and lots.

8.2 Cleaning of Apparatus and Test Components

8.2.1 Test Cylinders, As Received

8.2.1.1 Remove cylinders from protective covering.

8.2.1.2 Place cylinders hub side down in a clean 500 mL beaker. Transfer a sufficient volume of a 1 to 1 minxture of isooctane (Danger - see Annex A.1.2) and isopropyl alcohol (Warning - see Annex A.1.3) to the beaker such that the exposed surfaces of the test cylinders are completely covered.

8.2.1.3 Place beaker in ultrasonic cleaner and turn on for 15 minutes.

8.2.1.4 Remove cylinders and repeat ultrasonic cleaning cycles of Section 8.2.1.3 with a clean beaker and fresh solvents.

NOTE 1: Handle all clean cylinders with clean forceps or disposable gloves.

8.2.1.5 Remove cylinders from beaker and rinse with isooctane. Dry. Rinse with acetone (Danger - see Annex A.1.4).

8.2.1.6 Dry and store in a desiccator.

8.2.2 Test Balls, As Received.

8.2.2.1 Place balls in 300 mL beaker. Transfer a sufficient volume of a 1 to 1 mixture of isooctane and isopropyl alcohol to the beaker such that the test balls are completely covered by the cleaning solvent.

NOTE 2: Approximately a five-day supply can be processed at one time.

8.2.2.2 Place beaker in ultrasonic cleaner and turn on for 15 minutes.

8.2.2.3 Repeat the cleaning cycle of Section 8.2.2.2 with a clean beaker and fresh solvent.

[13] Additive shall be DCI-4A obtained from E.I. DuPont de Nemours & Company, 1007 Market Street, Wilmington, DE 19893.

[14] Solvent shall be Iso Par M obtained from the EXXON Company, USA, P.O. Box 2180, Houston, TX 77001.

8.2.2.4 Remove and rinse with isooctane. Dry. Rinse with acetone.

8.2.2.5 Dry and store in a desiccator.

8.2.3 Reservoir, Reservoir Cover, Ball Chuck, Ball Lock Ring

8.2.3.1 Rinse with isooctane.

8.2.3.2 Clean in an ultrasonic cleaner with a 1 to 1 mixture of isooctane and isopropyl alcohol for five minutes.

8.2.3.3 Remove and rinse with isooctane. Dry. Rinse with acetone.

8.2.3.4 Dry and store in a desiccator.

8.2.4 Hardware

8.2.4.1 The hardware and utensils, i.e. shaft, wrenches, tweezers, that come in contact with the test fluid shall be cleaned by washing thoroughly with isooctane and wiping with wiping tissue.

8.2.4.2 Store parts in desiccator when not in use.

8.2.5 After Test

8.2.5.1 Remove reservoir and cylinder.

8.2.5.2 Clean in an ultrasonic cleaner using a 1 to 1 mixture of isooctane and isopropyl alcohol for five minutes. Rinse with isooctane. Dry. Rinse with acetone.

8.2.5.3 Dry and store in a desiccator.

NOTE 3: When testing the same fluid, it may be considered sufficient to clean the reservoir in-place. The reservoir is rinsed with isooctane. Wipe with disposable wiper to remove residual fuel related deposits and test debris. The reservoir is rinsed again with isooctane. Dry and final rinse with acetone. Dry. Care shall be taken to ensure that the fuel aeration tube is rinsed and dried during the cleaning procedure. Store parts in desiccator when not in use.

NOTE 4: When testing the same fluid, it may be considered sufficient to clean the cylinder in-place. Rotate cylinder by switching on the motor drive and flush cylinder with isooctane. With an isooctane wetted disposable wiper, wipe cylinder surface. Loosen the cylinder set screw and thoroughly rinse the cylinder and shaft with isooctane. During the rinse cycle, the cylinder should be moved back and forth on the shaft to ensure that all surfaces are rinsed. Remove reservoir and pour waste solvent in waste fuel container. The flex lines to the reservoir are long enough to place reservoir to the side of the BOCLE rig during the next phase of cleaning. Use wipers to wipe recessed areas of BOCLE base plate below the cylinder and shaft. Take care that the micrometer probe is rinsed and dried during the cleaning procedure. Replace reservoir into recessed area of BOCLE base plate and rinse the cylinder, shaft, and micrometer probe with acetone. Remove and empty reservoir of waste solvent. Return reservoir to recessed area of base plate and turn motor control switch to "On" to allow to rotate to dry. Turn motor control switch to "Off".

9. Calibration and Standardization

9.1 Inspect cylinders and test balls under microscope before each tast. Eliminate specimens that contain pits, corrosion or surface abnormalities.

9.2 Standard Reference Fluid

9.2.1 Test each new batch of standard reference fluid per Section 10 with a test cylinder qualified with the previous standard reference fluid.

9.2.2 Repeat for two additional tests.

9.2.3 Further tests are necessary if the wear scar diameters differ by more than 0.03mm.

9.2.4 Obtain the average wear scar diameter (WSD). This is the standard reference fluid value.

9.3 Test Cylinder Calibration

9.3.1 Test each new cylinder with the standard reference fluid.

9.3.2 Repeat test if the wear scar diameter does not agree within 0.03mm WSD of the standard reference fluid value.

9.3.3 A third test shall be performed in the event the first two values obtained differ more than 0.03mm from each other.

9.3.4 The cylinder shall be rejected when the results differ by more than 0.03mm WSD from the standard reference fluid value or from its other tests.

9.4 Leveling of Load Arm

NOTE 5: The load arm level shall be inspected prior to every test.

9.4.1 Level the motor platform by use of the circular bubble level and adjustable stainless steel legs.

9.4.2 Install a test ball in the retaining nut as described in Section 10.4.

9.4.3 Lower load arm by use of disengaging blue pull pin. Apply 500 gram weight to end of load beam. Lower ball onto cylinder manually or by use of arm actuator switch.

9.4.4 Check level on top of load arm. The indicator bubble shall be centered in the middle of the two lines. If required adjust the retaining nut screw to achieve a level load arm.

10. Procedure

10.1 The summary of test conditions is included in Table Q-1.

10.2 Installation of Cleaned Test Cylinder

NOTE 6: The Ball-On-Cylinder Tester is very sensitive to contamination problems. The greatest care must be taken to adhere strictly to cleanliness requirements and to the specified cleaning procedures.

During handling and installation procedures, cleaned test parts (cylinders, balls, reservoir, and reservoir cover) must be protected from contamination by wearing clean throw-away "lint free" cotton gloves.

NOTE 7: Fluid shall be supplied in accordance with ASTM D4306.

10.2.1 Rinse shaft with isooctane and wipe with disposable wiper.

10.2.2 Adjust loading washers as shown in Figure Q-4.

10.2.3 Push the shaft through the left hand bearing and support bracket.

10.2.4 Hold the cylinder with the set screw hub facing left. Push the shaft through the cylinder bore, through the right hand bearing support bracket, and into the coupling as far as the shaft will go.

10.2.5 Align the coupling set screw with the flat keyway side of the cylinder shaft. Tighten set screw.

10.2.6 Set micrometer at zero (0) mm and slide cylinder to the left until it is firm against micrometer probe. Insure that cylinder set screw is directed toward the keyway (flat surface on shaft) and tighten set screw.

10.2.7 Back micrometer probe away from cylinder before drive motor is engaged.

10.3 Record on the Data Sheet(Figure Q-5)the cylinder number and the position of the test cylinder as indicated by the micrometer. The first and last wear tracks on a cylinder shall be approximately 1mm in from either side.

10.3.1 For subsequent tests, reset cylinder to a new test position with the micrometer. The new position should be 0.75mm from the last wear track on the cylinder and noted on the data sheet. After tightening the cylinder set screw to lock the cylinder in a new test position, the micrometer probe should be backed off, then advanced to the cylinder again. Check micrometer reading to ensure correct track spacing. Readjust position, if required. When the correct cylinder position is assured, back the micrometer probe away from the cylinder.

10.4 Install a clean test ball by first placing the ball in the retaining nut, followed by the blue retaining ring. Screw retaining nut onto the threaded chuck located on the load arm and hand tighten.

10.5 Secure the load beam in the "Up" position by insertion of the blue pin.

10.6 Install the clean reservoir. Install the blue spacing platform by raising the reservoir. Slide blue spacer platform into position under the reservoir. Place thermocouple in the hole provided at the rear left side of the reservoir.

10.7 Check load beam level. Adjust, if necessary.

10.8 Transfer 50 mL ± 1 mL of the test fluid to the reservoir. Do not allow fluid to contact shaft. Place cleaned reservoir cover in position and attach the 1/4" and 1/8" air lines to reservoir cover.

10.9 Move power switch to "On" position.

10.10 Turn on compressed air cylinder. Adjust the delivery pressure to 207-345 kPa (30-50 psi) and the console air pressure to approximately 100 kPa (14.5 psi).

10.11 Place arm lift actuator switch in the "Up" position.

10.12 Lower load beam by pulling blue pull pin. Hang standard 500g weight on end of load beam.

10.13 Start rotation of cylinder by switching motor drive to "On". Set rotation to 240 ± 1 r/min.

10.14 Using the flow meters that control the wet and dry air flows, adjust conditioned air flow to read 3.8 L/min. Maintain 10.0 ± 0.2 on the percent relative humidity readout.

10.15 Adjust reservoir temperature by consulting digital readout until temperature stabilizes at 25 ± 1°C. Adjust thermostat of the heat exchanger circulating bath to obtain the required temperature.

10.16 Adjust fuel aeration flowmeter to 0.5 L/min and set fuel aeration timer for 15 min.

10.17 At completion of aeration, the whistle will sound and aeration will cease. Continue 3.8 L/min flow through the reservoir. Move arm lift actuator switch to "Down" position. In approximately 8 seconds the load arm will be lowered and the ball will gently make contact with the cylinder. Switch timer "On" for 30 minutes.

NOTE 8: The rate at which the load arm lowers is controlled by the arm lift actuator valve on the left side of the cabinet. This valve controls the bleed off of the pneumatic arm lift actuator cylinder.

10.18. Check all test condition readouts and adjust as necessary. Record all necessary information on Data Sheet.

10.19 At the end of 30 minutes, the whistle will sound and the test load arm will automatically spring up. Turn timer to "Off" and move arm lift actuator switch to "Up" position.

10.20 Manually remove test weight. Lift test load arm up and secure with blue pull pin.

10.21 Remove reservoir cover and wipe revolving cylinder with a disposable wiper to remove residue from the test cylinder. Turn motor drive and power switch to "Off".

10.22 Pull the blue spacer platform from under the reservoir. Discard the fluid.

10.23 Remove test ball from locking nut. Do not remove ball from blue retaining ring. Wipe ball clean with disposable wiper prior to microscopic examination.

11. Measure of the Wear Scar

NOTE 9: The method is referred to as the Best Ellipse Method. The method interprets and measures the wear scars on the test balls allowing for the measurement of jagged and irregular wear scars.

11.1 Turn on microscope light and position test ball under microscope at 100X magnification.

11.2 Focus microscope and adjust stage such that wear scar is centered within the field of view. Adjust stage and occular such that the reticle scale is horizontal through the major axis of the wear scar.

11.3 Align the wear scar to a divisional point of reference on the numerical scale with the mechanical stage controls. On scars with irregular edges, measure to the point where the edge of the ellipse would be if the irregular edge were not present, as illustrated in Figure Q-6. Figures Q-7 and Q-8 are typical examples of wear scars. Measure the major axis to the nearest 0.01 mm. Record the readings on the Data Sheet.

11.4 Turn the occular until the reticle scale is vertical through the minor axis of the wear scar. Align the wear scar to a divisional point of reference on the numerical scale with the mechanical stage controls. Measure the minor axis to the nearest 0.01mm. Record the readings on the Data Sheet.

11.5 Record condition of wear area if different from the reference standard test, i.e., debris color, unusual particles or wear pattern, visible galling, etc., and presence of particles in the reservoir.

12. Calculations

12.1 Calculate the wear scar diameter as follows:

$$WSD = (M + N)/2$$

where: WSD = wear scar diameter, mm
M = major axis, mm
N = minor axis, mm

13. Report

13.1 Report the average wear scar diameter to the nearest 0.01mm.

13.2 Report the description of the wear scar area.

13.3 Report deviations from the standard conditions of the test load, relative humidity and fuel temperature, etc.

14. Precision and Bias

14.1 The precision of the method as determined by statistical examination of interlaboratory results according to ASTM RR: D02-1007 is as follows:

14.1.1 Repeatability - the difference between two test results obtained by the same operator with the same apparatus under constant operating conditions on identical test material would, in the long run, in the normal and correct operation of the test method, exceed the following values in only one case in twenty:

$$\text{Repeatability} = 0.489 \text{ (Wear Scar Diameter)}^{2.25}$$

A graphical representation is given in Figure Q-9.

14.1.2 Reproducibility - The difference between two single and independent results obtained by different operators working in different laboratories on identical test material would, in the long run, in the normal and correct operation of the test method, exceed the following value only in one case in twenty:

$$\text{Reproducibility} = 0.882 \text{ (Wear Scar Diameter)}^{2.25}$$

A graphical representation is given in Figure Q-9.

14.2 Bias - No statement can be made about the bias of this method for measuring lubricity since there is no standard material available for comparison.

TABLE Q-I

STANDARD OPERATING CONDITIONS

Fluid Volume	50 ± 1.0 mL
Fluid Temperature	25 ± 1^{o}C
Conditioned Air	10 ± 0.2% relative humidity at 25 ± 1^{o}C

Fluid Pretreatment 0.50 L/min flowing through and 3.3 L/min over the fluid for 15 minutes

Fluid Test Conditions 3.8 L/min flowing over the fluid

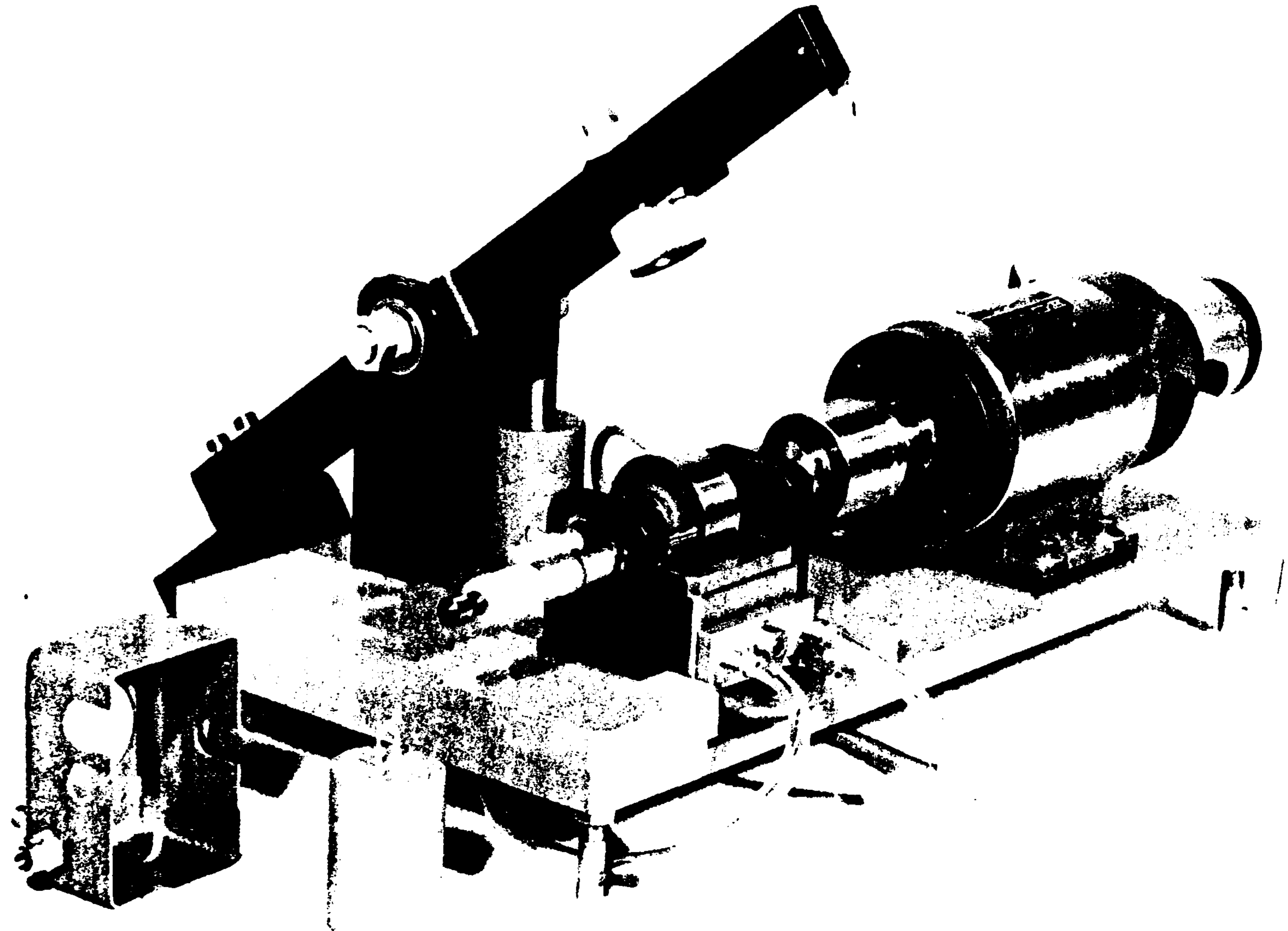
Ball Load	1000 g (500 g weight)
Cylinder Rotational Speed	240 ± 1 r/min
Test Duration	30 ± 0.05 minutes

FIGURE Q-1

Model BOC-100 Ball-on-Cylinder

LUBRICITY TESTER

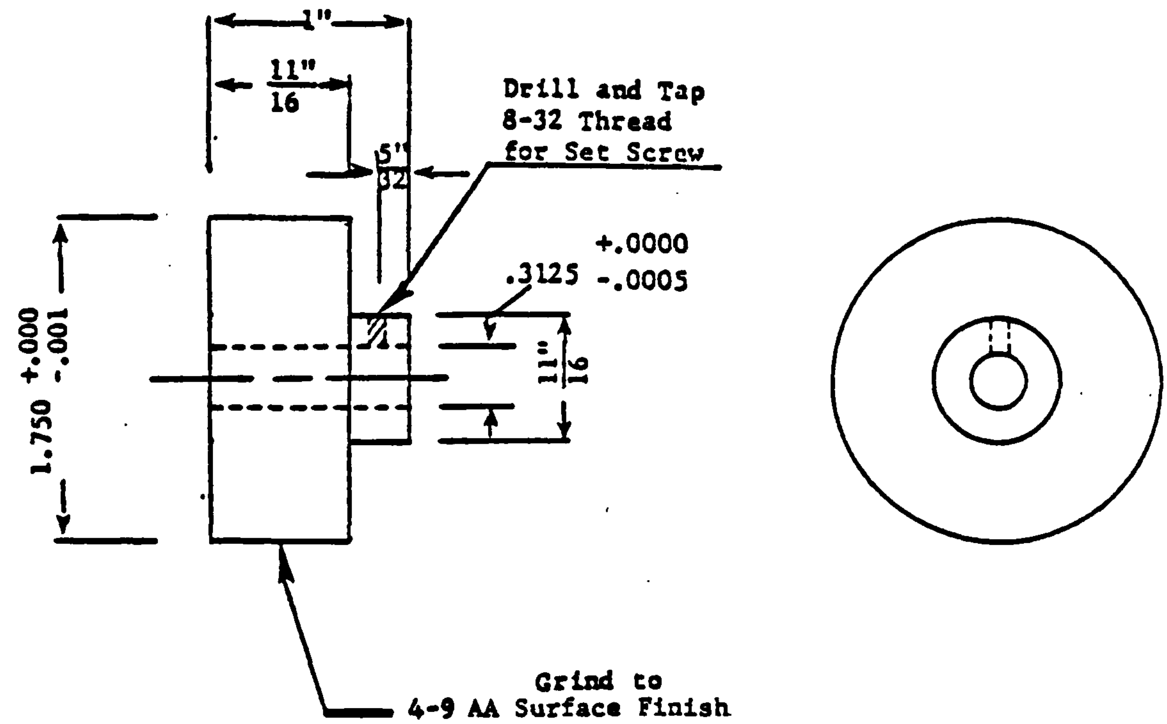
FIGURE Q-2



BALL-ON-CYLINDER LUBRICITY TESTER

FIGURE Q-3

CYLINDER FOR BALL-ON-CYLINDER LUBRICITY EVALUATOR



NOTES:

1. **Material**: AMS 6444
2. **Hardness**: 226-337 BHN (20-22 Rc)

FIGURE Q-4

CYLINDER INSTALLATION

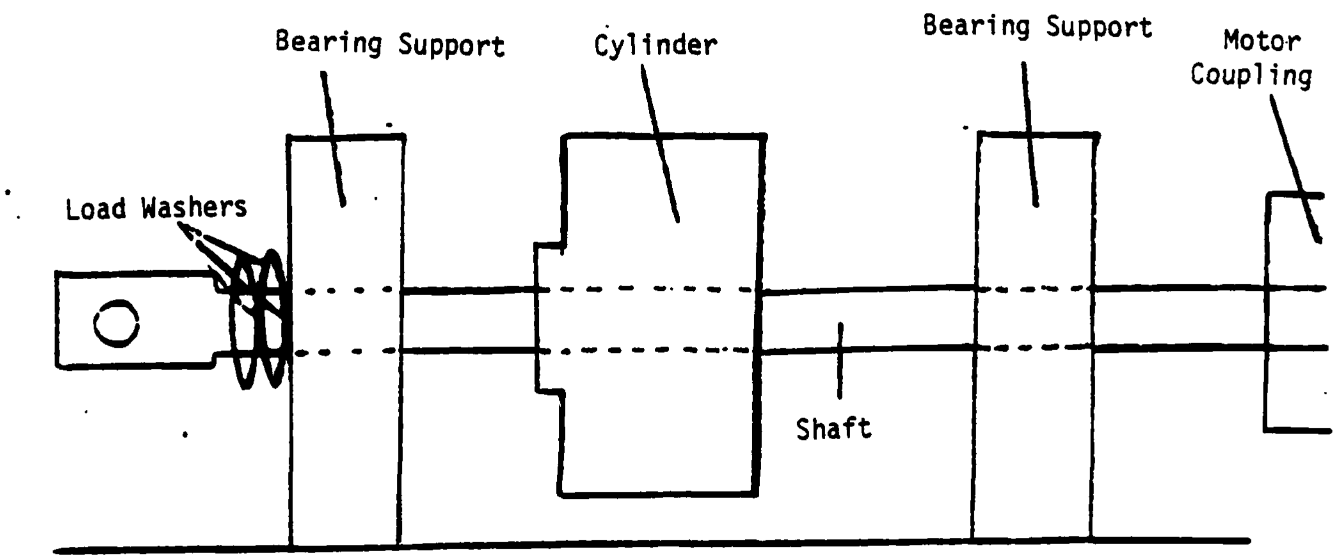


FIGURE Q-5

BALL-ON-CYLINDER LUBRICITY DATA

LABORATORY ____________ DATA SHEET NO. ____________

LOAD ____________ CYLINDER NUMBER ______ HARDNESS ______
CYLINDER NUMBER ______ HARDNESS ______

Test No.	Sample No. POSF-	Date/ Time	Cylin-der No.	Track No.	Fuel Temp. °C	Rel. Hum., %	Wear Scar Dia. Major, mm	Wear Scar Dia. Minor, mm	Track Width, mm	Comments/Wear Condition
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										
13										
14										
15										
16										
17										
18										
19										
20										
21										
22										

FIGURE Q-6

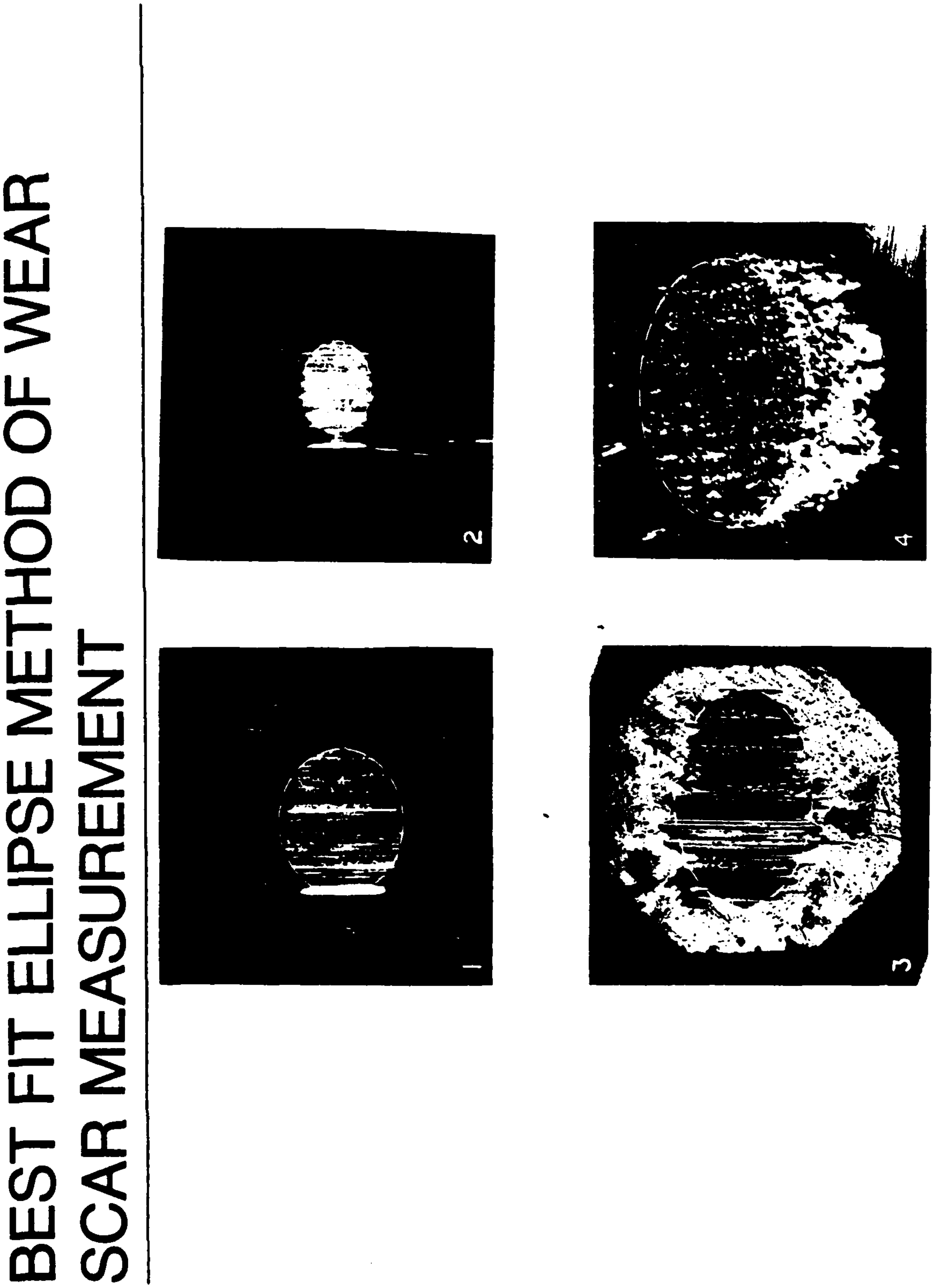


FIGURE Q-7

EXAMPLE OF AN ALMOST PERFECT ELLIPTICAL WEAR SCAR

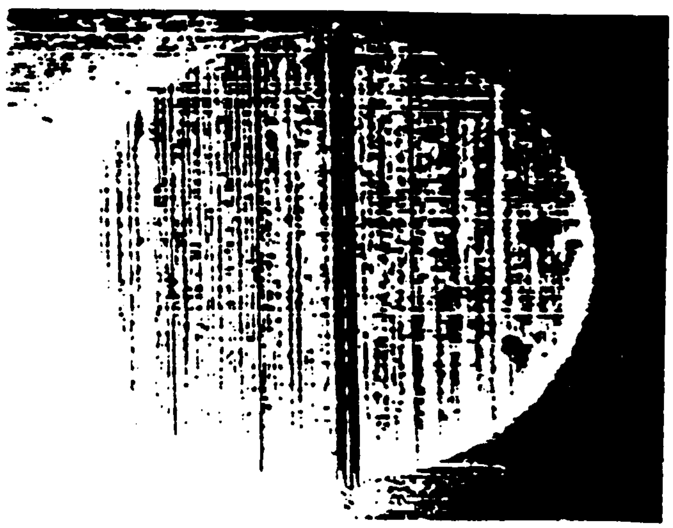


FIGURE Q-8

TYPICAL WEAR SCARS

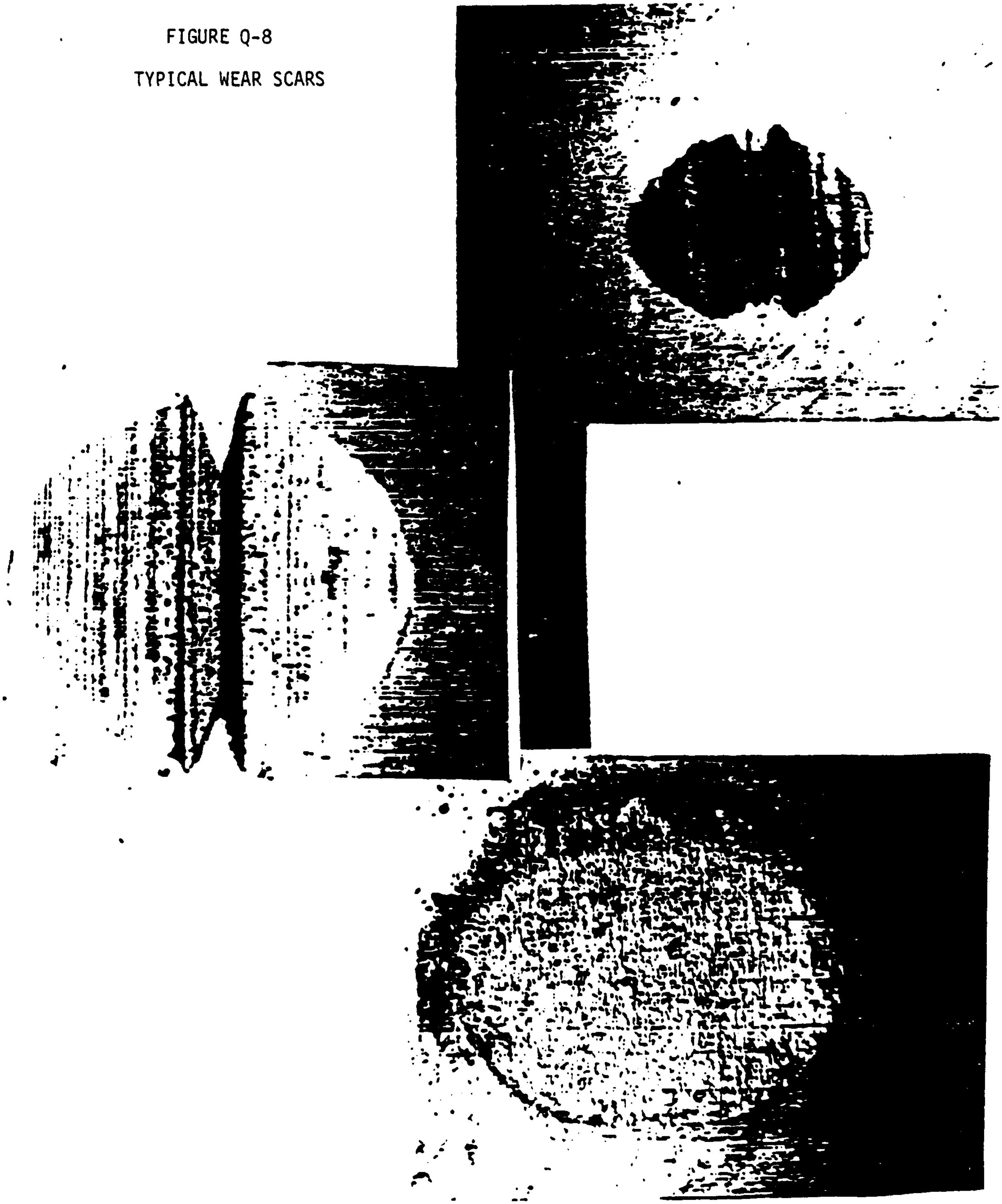
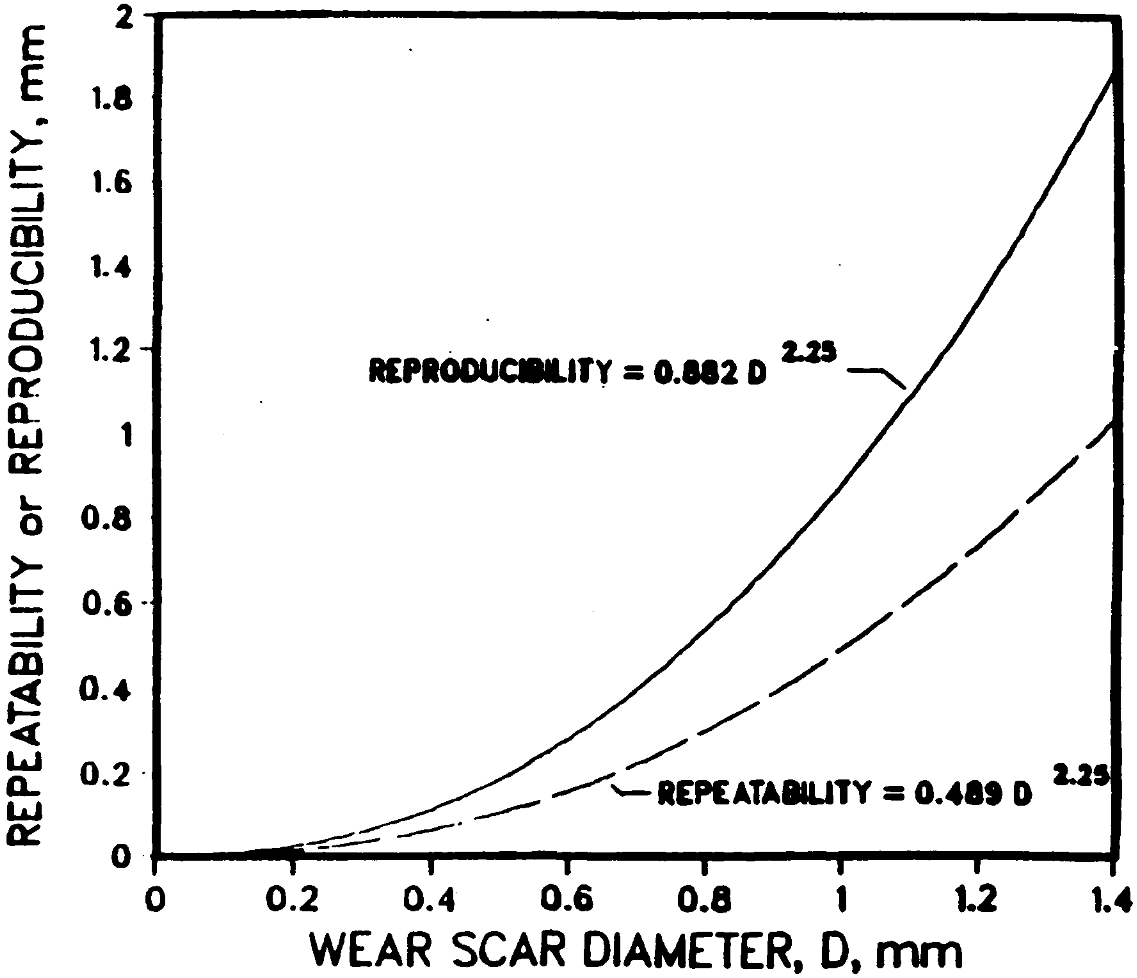


FIGURE Q-9

BOCLE ROUND-ROBIN II PRECISION



ALTERNATE METHOD

1A. Scope - See Section 1.

2A. Applicable Documents - See Section 2.

3A. Terminology - See Section 3.

4A. Summary of Method - See Section 4.

5A. Significance and Use - See Section 5.

6A. Apparatus

6A.1 Ball-on-Cylinder Lubricity Evaluator described in detail in Annex A2 and illustrated in Fig. 1A and 2A.[15]

6A.2 Atmosphere Control Unit, described in detail in Annex A3.

6A.3 Hygrometer, capable of determining a relative humidity of 10 + 0.2% in a 25 ± 1°C temperature air stream flowing at 3.8 L/min (8 SCFH).[16]

6A.4 Timing Device, capable of measuring time to 1 second.

6A.5 Tachometer, capable of measuring the cylinder shaft rotation at the 240r/min with an accuracy of ± 1r/min.

6A.6 Rotometer, capable of measuring the gas volume at the 3-4 L/min flow with an accuracy of ± 0.05% (for alternate air flow measurement).

6A.7 Soxhlet Extractor, extraction chamber 40mm ID minimum with 500mL flask or larger (alternate cleaning method).

6A.8 Wet Test Meter, capable of measuring the gas volume at the 3-4 L/min flow with an accuracy of 0.05%.[17]

6A.9 See Section 6.2, 6.3 and 6.4.

7A. Reagents and Materials - see Section 7.

8A. Preparation of Apparatus - see Section 8.

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[15] Evaluator design originated by Exxon Research and Engineering Co. and modifications incorporated by Woodward Governor Co.

[16] Dew Point Hygrometer System 1100DP from General Eastern Instrument Corp.; 50 Hunt Street, Watertown, MA 02172 has been found satisfactory.

[17] Precision Scientific Model 63111 or 63119 wet test meter has been found satisfactory.

ALTERNATE METHOD

8A.1A Test Cylinders, As Received - Alternate Method

8A.1A.1 Remove cylinders from protective covering.

8A.1A.2 Rinse well in isooctane.

8A.1A.3 Wash with detergent solution.

8A.1A.4 Rinse thoroughly in distilled water.

NOTE 1A: Handle all cleaned surfaces with clean forceps or gloves.

8A.1A.5 Dry in an oven at 125-150°C until free of water.

8A.1A.6 Clean in a Soxhlet Extractor using a 1 to 1 mixture of isopropyl alcohol and isooctane. Reflux for 15 cycles or two hours, whichever is greater.

8A.1A.7 Dry and store in a desiccator.

8A.2A Test Balls, As Received - Alternate Method

8A.2A.1 Same as Section 8A.1A.

9A. Calibration and Standardization - See Section 9.1, 9.2 and 9.3

10A. Procedure

10A.1 Install test reservoir bottom.

See Note 6

10A.2 Hold the cylinder with the set screw hub facing left. Push the cylinder shaft through the left hand bearing support bracket, the cylinder bore, the right hand bearing support bracket, and into the flex coupling.

10A.3 Tighten set screw in test cylinder. Adjust cylinder positioning by means of the micrometer and tighten set screw of shaft flex coupling. Recheck micrometer setting to verify correct cylinder spacing.

10A.4 Slip the vapor line onto inlet tube on the test reservoir.

10A.5 Insert temperature probe in the base of the reservoir.

10A.6 Record on the Data Sheet (Figure 5) the cylinder number and the position of the test cylinder. The first and last wear tracks on a cylinder shall be approximately 1mm in from either side.

10A.6.1 For subsequent tests, reset cylinder to a new test position 0.75mm from the last wear track on the cylinder and note on the data sheet.

10A.7 Place a clean test ball in the ball retaining nut. Thread nut onto holder on beam until finger tight, then use a cleaned open end wrench to tighten nut.

ALTERNATE METHOD

10A.8 Check load arm level. Adjust, if necessary.

10A.9 Transfer 50 mL ± 1 mL of the test fuel to the reservoir. The standard operating conditions of the BOCLE test are given in Table 1. See Note 7.

10A.10 Place cover on the reservoir.

10A.11 Flow the 10% relative humidity air 3.8 L/min through the fuel and reservoir chamber with the fuel receiving 0.5L/min of the flow. Continue the humidity adjustment for 15 minutes.

10A.12 Cease the air flow through the fuel and continue the 3.8 L/min flow through the reservoir for the duration of the test.

10A.13 Lower beam and place ball onto cylinder.

10A.14 Lower beam lifter. Set roation switch on controller to 240± 1 r/min. and monitor with the tachometer.

10A.15 Monitor reservoir temperature until temperature stabilizes at 25 ± 1°C. Adjust thermostat of the heat exchanger circulating bath to obtain the required temperature.

10A.16 Attach the 500g load to the beam.

See Note 8.

10A.17 Turn power switch to "ON" and push "START" button.

10A.18 Raise the beam lifter to the "UP" position. The ball will contact cylinder. START the timer.

10A.19 Lift beam after 30 ± 0.05 minutes.

10A.20 Raise beam. Remove reservoir cover.

10A.21 Loosen the ball retaining nut on the beam. Lower beam close to the horizontal and unscrew the nut being careful to remove the nut without the wear scar on the ball disappearing from view.

10A.22 With the ball in the lower half of the nut, press a ball holder onto the top of the ball. Wipe ball clean with disposable wiper prior to microscopic examination.

10A.23 Remove reservoir and discard the fluid.

10A.24 Clean evaluator as described in Section8.2 before the next test.

11A. Measurement of Wear Scar - See Section 11.

12A. Calculations - See Section 12.

13A. Report - See Section 13.

14A. Precision and Bias - See Section 14.

ANNEX

(Mandatory Information)

A1. PRECAUTIONARY STATEMENTS

A1.1 Compressed Air (cylinder)

Caution—Compressed gas under high pressure. Use with extreme caution in the presence of combustible material, since the autoignition temperatures of most organic compounds in air are drastically reduced at elevated pressures.

Keep cylinder valve closed when not in use.

Always use a pressure regulator. Release regulator tension before opening cylinder.

Do not transfer to cylinder other than one in which air is received. Do not mix gases in cylinder.

Do not drop cylinder. Make sure cylinder is supported at all times.

Stand away from cylinder outlet when opening cylinder valve.

Keep cylinder out of sun and away from heat.

Keep cylinders from corrosive environment.

Do not use cylinder without label.

Do not use dented or damaged cylinders.

For technical use only. Do not use for inhalation purposes.

A1.2 *Isooctane*

Danger—Extremely flammable. Harmful if inhaled. Vapors may cause flash fire.

Keep away from heat, sparks, and open flame.

Keep container closed.

Use with adequate ventilation.

Avoid build-up of vapors and eliminate all sources of ignition, especially nonexplosion-proof electrical apparatus and heaters.

Avoid prolonged breathing of vapor or spray mist.

Avoid prolonged or repeated skin contact.

A1.3 Isopropyl Alcohol

Warning—Flammable.

Keep away from heat, sparks, and open flame.

Keep container closed.

Use with adequate ventilation.

Avoid prolonged breathing of vapor or spray mist.

Avoid contact with eyes and skin.

Do not take internally.

A1.4 Acetone

Danger—Extremely flammable. Vapors may cause flash fire.

Keep away from heat, sparks, and open flame.

Keep container closed.

Use with adequate ventilation.

Avoid build-up of vapors, and eliminate all sources of ignition, especially nonexplosion-proof electrical apparatus and heaters.

Avoid prolonged breathing of vapor or spray mist.

Avoid contact with eyes or skin.

ANNEX

A2. Ball-On-Cylinder Lubricity Evaluation (BOCLE)

A2.1 The BOCLE (Figure 2A) consists of a non-rotating 12.7mm diameter steel ball (A) held in a vertically mounted chuck (B) and forced against the highest point on the outer surface of a 44.45mm diameter steel cylinder (C). Details of the cylinder are in Figure 3.

A2.2 The ball and cylinder are positioned inside a rectangular reservoir (D) that contains a sufficient amount (50 mL) of test fluid to cover the bottom portion of the cylinder.

A2.3 The cylinder is axially mounted on a horizontal shaft (E) that passes through the sides of the reservoir and is connected to a variable speed motor.

A2.4 Holes drilled in the base and side of the reservoir (G) allow purge gas of 10% relative humidity air to be bubbled over and through the test fluid. The humidity of the purge gas is controlled by volumetrically mixing dry gas and moisture saturated gas (bubbled through two water filled spargers in series) in the required proportion .

A2.5 The load is applied to the cylinder by a 500 gram hanging weight on the hook (H) at the end of the balance beam (J). The balance beam is designed so that the ball is located exactly midway between the pivot point (K) and the mass hook (H). This makes the vertical load on the ball equal to twice the load applied at the mass hook.

A3. Atmosphere Control Unit

A3.1 The atmosphere control unit (Figure 3A) provides the precisely controlled environment for the BOCLE test.

A3.2 The system consists of the dry air flow from the supply cylinder (A) which is split into two portions, each with its flow valve (B).

A3.3 The air flow in one portion goes directly to the flowmeter (C).

A3.4 The air from the second portion flows through the humidifier (D) to the flowmeter (C).

A3.5 The two portions of air are again united and progress through the wet test meter (E) or rotometer for final flow measurement at 3.8 L/min (8 SCFM).

A3.6 The air flows through the constant temperature bath-circulator (F) to obtain the 25 ± 0.5°C temperature which is then monitored by the hygrometer (G) at 10 ± 0.2% relative humidity.

A3.7 The air flow is ready for attachment to the reservoir inlets when the flow rate, temperature, and relative humidity meet the required conditions.

A3.8 Relative humidity adjustment.

A3.8.1 The flow rate for each air flow portion is approximated as follows:

$$\text{Total air flow} \times \frac{\text{relative humidity}}{100} = \text{wet portion flow}$$

Total flow - wet portion flow = dry portion flow

For the conditions specified in A3.5 and A3.6 this is 0.38L/min for the wet portion and 3.40 L/min for the dry portion.

A3.8.2 The final adjustments to the air flow proportions are made based on the readings obtained on the hygrometer.

FIGURE Q-1A

BALL-ON-CYLINDER LUBRICITY EVALUATOR

EXXON/WOODWARD

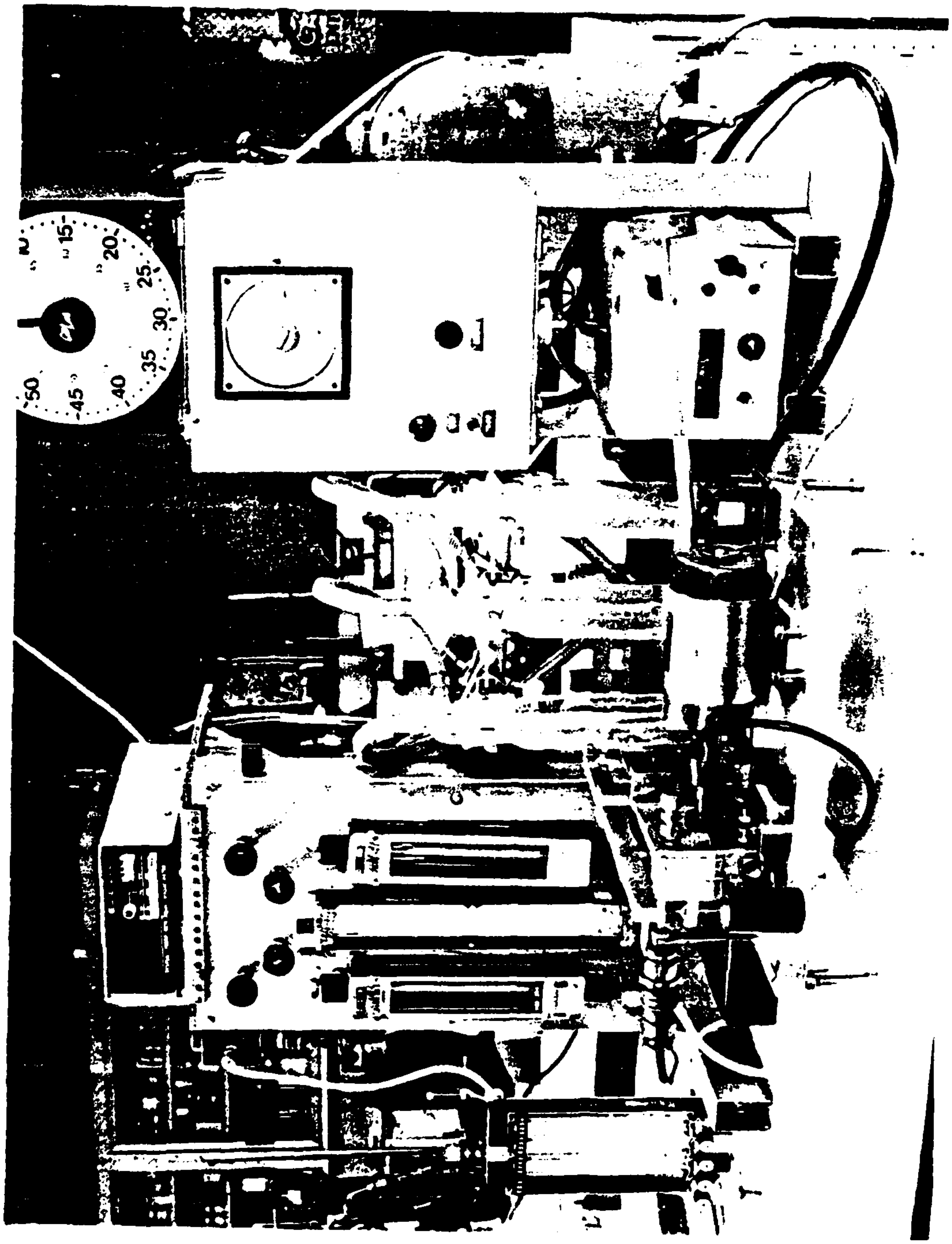


FIGURE Q-2A

SCHEMATIC OF BALL-ON-CYLINDER LUBRICITY EVALUATOR (BOCLE)

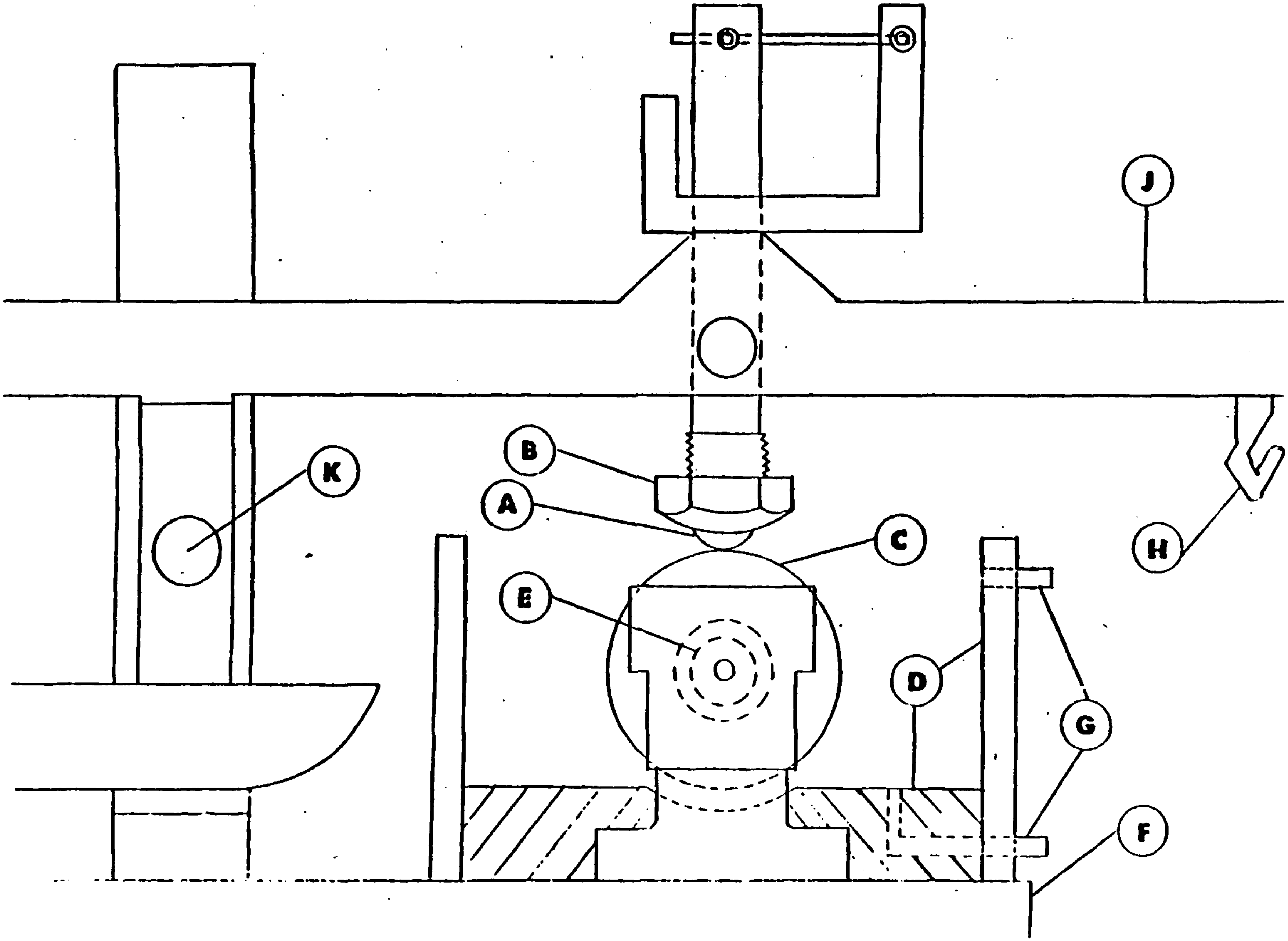
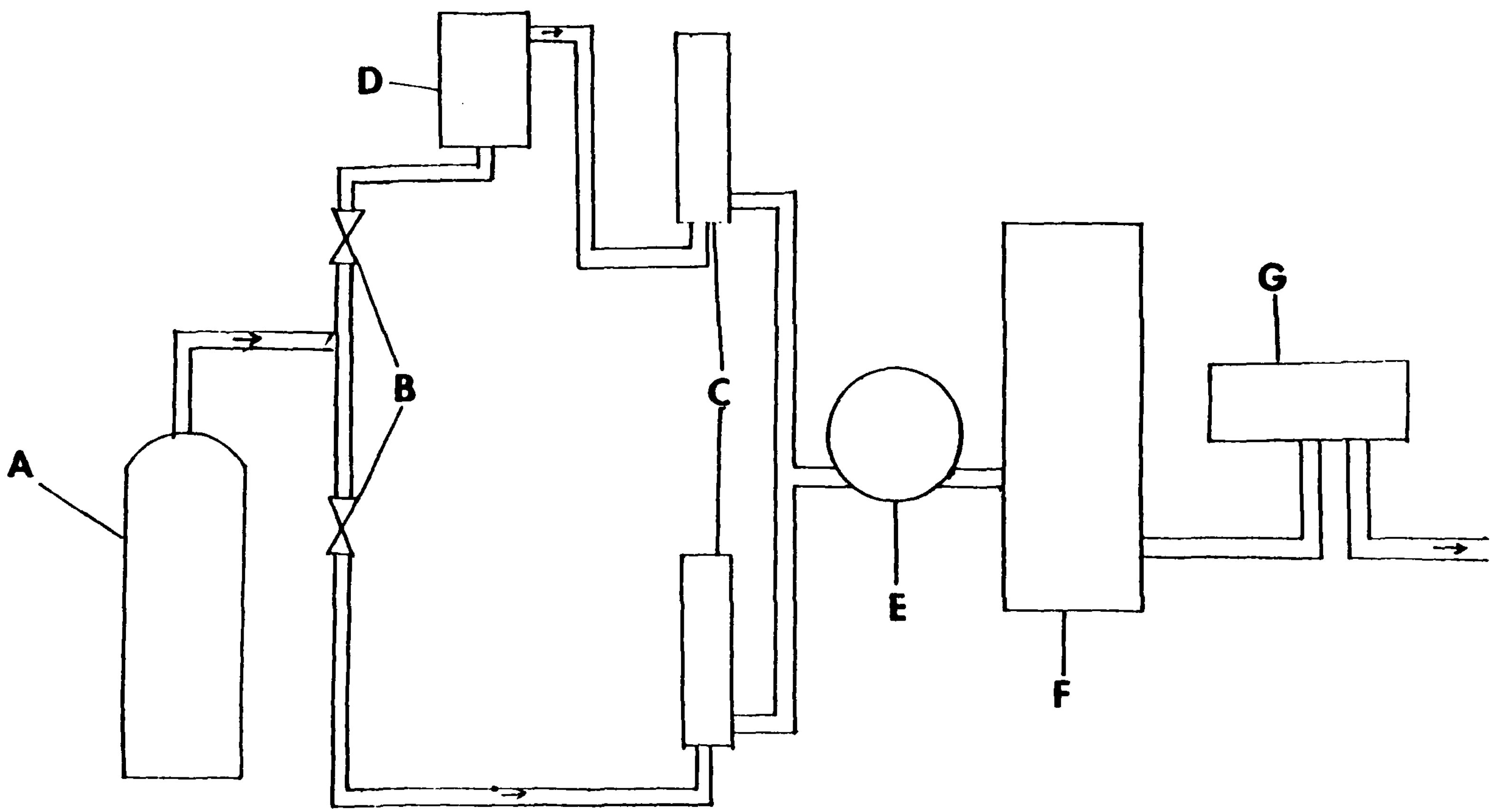


FIGURE Q-3A

SCHEMATIC OF ATMOSPHERE CONTROL UNIT



APPENDIX R

COMPARISON OF BOCLE RESULTS

APPENDIX R

COMPARISON OF BOCLE RESULTS FOR VARIOUS FUELS-TEST CYLINDER/ TEST RING

Fuel Type	Nominal WSD, mm		Marginal WSD, mm	
	Test Ring	Conventional	Test Ring	Conventional
JP-4	0.550	0.30	0.600	0.40
JP-5	0.510	0.30	0.560	0.40
JP-7	0.690	0.40	0.740	0.50
JET A	0.510	0.30	0.560	0.40
*JP-8	0.560		0.610	
CT JP-4	0.920	0.60		

Reference Fluid: ISOPAR M + 30 ppm DC14A

*Limited data available on JP-8

APPENDIX S

EFFECT OF SURFACE FINISH ON WSD WITH TEST RINGS

APPENDIX S

EFFECT OF SURFACE FINISH ON WSD WITH TEST RINGS

I. SURFACE FINISH GROUP: 8-12 RMS

Surface Finish & Ring No.	WSD Isopar M + DCI-4A Run #1	Run #2	X	WSD Neat Isopar M Run #1	Run #2	X
12-(1)	0.425	0.470	0.448	0.720	0.695	0.708
11-(2)	0.420	0.450	0.435	0.710	0.765	0.738
12-(3)	0.455	0.470	0.463	0.715	0.740	0.728
12-(4)	0.465	0.455	0.460	0.730	0.730	0.730
12-(5)	0.465	0.460	0.463	0.740	0.760	0.750

$\bar{X}$ All Runs: 0.453, sd = 0.019

$\bar{X}$ All Runs = 0.727, sd = 0.020

II. SURFACE FINISH GROUP: 37-43 RMS

Surface Finish & Ring No.	WSD Isopar M + DCI-4A Run #1	Run #2	X	WSD Neat Isopar M Run #1	Run #2	X
41-(1)	0.560	0.535	0.548	0.770	0.800	0.785
40-(2)	0.550	0.560	0.555	0.775	0.770	0.773
40-(3)	0.530	0.535	0.533	0.750	0.790	0.770
41-(4)	0.530	0.550	0.540	0.775	0.770	0.773
43-(5)	0.555	0.550	0.552	0.775	0.775	0.775

$\bar{X}$ All Runs: 0.545, sd = 0.013

$\bar{X}$ All Runs: 0.775, sd = 0.014

III. SURFACE FINISH GROUP: 20-30 RMS STANDARD SPECIFICATION

Surface Finish & Ring No.	WSD Isopar M + DCI-4A	WSD Neat Isopar M
25-(1)	0.500	0.770
25-(2)	0.490	0.760
25-(3)	0.485	0.750
27-(4)	0.495	0.755
27-(5)	0.485	0.765

$\bar{X}$ All Runs: 0.493, sd = 0.006

$\bar{X}$ All Runs = 0.759, sd = 0.009

A P P E N D I X   T

BOCLE MINI-ROUND-ROBIN III TEST DETAILS

APPENDIX T

BOCLE MINI-ROUND-ROBIN III TEST DETAILS

The test method will follow the method of Appendix Y except for the necessary deviations required by the change of the test configuration.

The test cylinders shall be replaced with test rings. The modification requires shims and a mandrel obtained from Falex Corporation. Three different lots shall be tested.

Each of the four test fuels shall be run in triplicate with two rings from each of the three lots of test rings.

The test balls shall be SKF Sweden RB 12.7.

The wear scar diameter shall be measured to the nearest 0.005 mm.

A P P E N D I X   U

BOCLE MINI-ROUND-ROBIN III

SUMMARY OF INDIVIDUAL WSD RESULTS

APPENDIX U

BOCLE MINI-ROUND-ROBIN III SUMMARY OF INDIVIDUAL WSD RESULTS

(ISOPAR M + 30 PPM DCI-4A)

Lot Design	Ring No.	Run No.	Pratt & Whitney	Woodward Governor	Chevron	Rolls Royce	WPAFB
K	1	1	0.510	0.510	0.510	0.496	0.500
	1	2	0.485	0.520	0.510	0.510	0.505
		3	0.485	0.520	0.530	0.507	0.505
	2	1	0.490	0.520		0.504	0.500
		2	0.495	0.530		0.481	0.510
		3	0.490	0.530		0.511	0.520
KX	1	1	0.500	0.530	0.510	0.499	0.510
		2	0.510	0.540	0.500	0.506	0.530
		3	0.520	0.520	0.520	0.488	0.510
	2	1	0.490	0.510		0.479	0.525
		2	0.505	0.510		0.501	0.490
		3	0.515	0.520		0.473	0.515
L	1	1	0.475	0.530	0.510	0.476	0.530
		2	0.485	0.530	0.520	0.500	0.510
		3	0.485	0.540	0.540	0.515	0.525
	2	1	0.520	0.530		0.477	0.515
		2	0.525	0.540		0.521	0.490
		3	0.515	0.520		0.501	0.525
Mean			0.500	0.525	0.517	0.497	0.512
Standard Deviation			0.015	0.010	0.012	0.015	0.012
Range			0.050	0.030	0.040	0.048	0.040

APPENDIX U

BOCLE MINI-ROUND-ROBIN III SUMMARY OF INDIVIDUAL WSD RESULTS

(ISOPAR M)

Lot Design	Ring No.	Run No.	Pratt & Whitney	Woodward Governor	Chevron	Rolls Royce	WPAFB
K	1	1	0.840	0.840	0.820	0.804	0.790
		2	0.820	0.860	0.800	0.824	0.805
		3	0.845	0.850	0.820	0.808	0.820
	2	1	0.825	0.830		0.827	0.790
		2	0.835	0.840		0.823	0.825
		3	0.830	0.830		0.814	0.795
KX	1	1	0.860	0.840	0.800	0.862	0.820
		2	0.840	0.860	0.800	0.803	0.810
		3	0.845	0.860	0.810	0.855	0.790
	2	1	0.850	0.840		0.829	0.795
		2	0.845	0.840		0.800	0.810
		3	0.840	0.840		0.833	0.830
L	1	1	0.840	0.840	0.830	0.826	0.815
		2	0.855	0.850	0.820	0.812	0.790
		3	0.855	0.850	0.820	0.824	0.795
	2	1	0.810	0.850		0.812	0.800
		2	0.810	0.850		0.817	0.820
		3	0.830	0.860		0.820	0.790
Mean			0.838	0.846	0.813	0.822	0.805
Standard Deviation			0.014	0.010	0.011	0.016	0.014
Range			0.050	0.030	0.030	0.062	0.040

APPENDIX U

BOCLE MINI-ROUND-ROBIN III SUMMARY OF INDIVIDUAL WSD RESULTS

(JP-4)

Lot Design	Ring No.	Run No.	Pratt & Whitney	Woodward Governor	Chevron	Rolls Royce	WPAFB
K	1	1	0.565	0.570	0.590	0.586	0.555
		2	0.565	0.570	0.580	0.595	0.560
		3	0.565	0.580	0.570	0.597	0.555
	2	1	0.560	0.570		0.564	0.560
		2	0.575	0.570		0.568	0.570
		3	0.570	0.570		0.585	0.575
KX	1	1	0.555	0.600	0.580	0.616	0.575
		2	0.565	0.580	0.570	0.553	0.565
		3	0.555	0.600	0.590	0.593	0.560
	2	1	0.575	0.590		0.580	0.540
		2	0.560	0.590		0.570	0.565
		3	0.560	0.590		0.588	0.555
L	1	1	0.545	0.590	0.590	0.582	0.585
		2	0.555	0.580	0.580	0.577	0.565
		3	0.565	0.570	0.580	0.561	0.565
	2	1	0.570	0.570		0.584	0.570
		2	0.570	0.580		0.567	0.555
		3	0.575	0.580		0.581	0.575
Mean			0.564	0.581	0.581	0.580	0.564
Standard Deviation			0.008	0.011	0.008	0.015	0.010
Range			0.030	0.030	0.020	0.063	0.045

APPENDIX U

BOCLE MINI-ROUND-ROBIN III SUMMARY OF INDIVIDUAL WSD RESULTS

(CLAY TREATED SHALE JP-4)

Lot Design	Ring No.	Run No.	Pratt & Whitney	Woodward Governor	Chevron	Rolls Royce	WPAFB
K	1	1	0.855	0.900	0.930	0.777	0.800
		2	0.855	0.910	0.900	0.815	0.795
		3	0.835	0.920	0.890	0.847	0.785
	2	1	0.865	0.930		0.844	0.740
		2	0.835	0.910		0.823	0.790
			0.825	0.930		0.773	0.775
KX	1	1	0.860	0.920		0.844	0.775
		2	0.830	0.890	0.880	0.815	0.765
		3	0.825	0.920	0.880	0.851	0.760
	2	1	0.870	0.930		0.833	0.740
		2	0.850	0.920		0.854	0.735
		3	0.845	0.910		0.839	0.745
L	1	1	0.855	0.920	0.930	0.819	0.730
		2	0.845	0.910	0.860	0.810	0.715
		3	0.845	0.920	0.940	0.840	0.710
	2	1	0.820	0.900		0.822	0.760
		2	0.830	0.910		0.812	0.760
		3	0.830	0.910		0.856	0.750
Mean			0.843	0.914	0.901	0.826	0.757
Standard Deviation			0.015	0.011	0.029	0.024	0.026
Range			0.050	0.040	0.080	0.083	0.090

APPENDIX V

BOCLE ROUND-ROBIN III TEST DETAILS

APPENDIX V

BOCLE ROUND-ROBIN III TEST DETAILS

The BOCLE shall be modified according to Figure 19 as follows:

1. Remove 6 Allen head screws that secure base plate to top plate.

2. Remove 4 Allen head screws that secure load beam pedestal to top plate.

3. Insert 1 1/2" x 3" shim between load beam pedestal to top plate.

4. Replace 4 Allen head securing screws.

5. Reattach top plate to base plate.

6. Attach 3/4" x 3/4" shim to underside of load beam in such a position that hydraulic lift plunger hits shim on UP position.
   NOTE: Contact cement has been found to be satisfactory for shim attachment to load beam.

7. Check load beam balance and adjust if required.

Two different lots of Timken test cups specified according to ASTM Test Method D2782 shall be used for test program.

The test balls shall be SKF Sweden RB 12.7. All test balls shall be examined under a microscope at 100X prior to use. Balls exhibiting inclusions or pits shall be discarded.

The test procedure shall be as described in Appendix Q, revised as follows:

Timken cup and mandrel assembly:

Par. 8.2.1 Initial cleaning of the Timken cup, as received from vendor

(a) Manually remove the preservative oil film from the test cup by scrubbing with a rag or paper towel saturated with isooctane.

(b) After all visible traces of the preservative oil have been removed, ultrasonic clean using equal volumes of isooctane and isopropyl alcohol. Ultrasonic cleaning should be maintained for a period of 15 minutes. Replace cleaning solvent with fresh solvent and continue ultrasonic cleaning for a second 15 minute cycle.

(c) Remove test cup, flush thoroughly using isooctane and blow dry with dry hydrocarbon-free compressed air. Repeat rinse procedure using acetone and blow dry.

(d) Test cup is now ready for use on previously cleaned mandrel assembly.

Par. 8.2.1.1 Cleaning of Timken cup and mandrel between tests Ultrasonic method:

(a) Remove shaft and cup/mandrel assembly from BOCLE and clean by ultrasonic as previously described.

(b) Remove shaft and cup/mandrel assembly from BOCLE and clean by thorough rinsing with isooctane (1-L squeeze bottles have been found adequate for dispensing cleaning solvents).

(c) Thoroughly dry cup/mandrel assembly using a jet of dry compressed air. Particular attention must be given to the air-drying of crevices described.

(d) Flush cup/mandrel assembly with acetone and blow dry as previously described.
NOTE: It is of utmost importance that the air jet used for drying be delivered at a maximum of 30 psig. The crevices of the cup/mandrel assembly are difficult to thoroughly dry at lower air pressures.

Starting micrometer setting should be 0.0 mm and runs spaced at intervals of 0.75 mm.

Each of the nine fuels shall be run once with each of the test cups at applied loads of 500 grams and 1000 grams.

APPENDIX W

BOCLE ROUND-ROBIN III

INDIVIDUAL LABORATORY RESULTS

APPENDIX W

BOCLE ROUND-ROBIN III INDIVIDUAL LABORATORY RESULTS

(500 Gram Load)

Fuel Sample	Ring No.	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U*
		LABORATORIES																				
C.T. JP4	1	0.790	0.716	0.670	0.716	0.665	0.760	0.740	0.730	0.715	0.645	0.675	0.735	0.680	0.665	0.790	0.714	0.720	0.710	0.700	0.764	0.665
	2	0.785	0.716	0.670	0.760	0.675	0.845	0.780	0.770	0.715	0.660	0.680	0.765	0.715	0.665	0.795	0.689	0.720	0.732	0.675	0.774	0.678
ISOPAR M	1	0.735	0.757	0.730	0.744	0.615	0.670	0.750	0.750	0.760	0.675	0.730	0.775	0.650	0.730	0.765	0.746	0.750	0.753	0.750	0.756	0.750
	2	0.730	0.752	0.750	0.769	0.675	0.690	0.740	0.765	0.780	0.700	0.725	0.700	0.705	0.705	0.780	0.717	0.730	0.706	0.775	0.743	0.750
C.T. JET A	1	0.705	0.711	0.710	0.803	0.705	0.715	0.790	0.750	0.730	0.695	0.640	0.805	0.670	0.730	0.800	0.738	0.730	0.750	0.708	0.750	0.765
	2	0.715	0.726	0.690	0.803	0.750	0.815	0.800	0.735	0.750	0.705	0.740	0.675	0.690	0.720	0.775	0.683	0.730	0.722	0.675	0.722	0.763
JET A	1	0.485	0.508	0.495	0.540	0.460	0.480	0.510	0.520	0.490	0.460	0.510	0.505	0.500	0.500	0.515	0.481	0.510	0.489	0.525	0.477	0.455
	2	0.485	0.513	0.505	0.530	0.475	0.500	0.520	0.520	0.500	0.465	0.475	0.500	0.530	0.485	0.510	0.483	0.510	0.500	0.500	0.492	0.453
JP-7	1	0.835	0.808	0.760	0.839	0.675	0.775	0.890	0.800	0.800	0.705	0.720	0.770	0.770	0.760	0.835	0.819	0.820	0.854	0.775	0.757	0.773
	2	0.825	0.798	0.790	0.805	0.745	0.855	0.830	0.770	0.815	0.645	0.740	0.750	0.790	0.770	0.825	0.755	0.820	0.783	0.725	0.821	0.763
JP-4	1	0.470	0.503	0.500	0.490	0.450	0.475	0.530	0.500	0.480	0.495	0.440	0.500	0.530	0.470	0.505	0.478	0.530	0.491	0.450	0.493	0.463
	2	0.480	0.528	0.495	0.498	0.460	0.515	0.490	0.520	0.465	0.500	0.465	0.490	0.510	0.500	0.505	0.475	0.520	0.499	0.525	0.510	0.460
JP-5	1	0.500	0.523	0.550	0.532	0.480	0.505	0.530	0.490	0.525	0.500	0.460	0.545	0.530	0.510	0.510	0.497	0.530	0.521	0.500	0.506	0.488
	2	0.505	0.518	0.545	0.537	0.480	0.510	0.520	0.510	0.495	0.525	0.465	0.510	0.540	0.530	0.520	0.509	0.530	0.520	0.500	0.518	0.495
JET A-1, UK-1	1	0.590		0.580	0.621			0.610	0.610	0.602							0.578	0.620	0.643	0.612	0.600	
	2	0.595		0.575	0.629			0.610	0.590	0.605							0.567	0.610	0.634	0.625	0.616	
JET A-1, UK-2	1	0.715		0.650	0.721			0.680	0.710	0.705							0.699	0.743	0.739	0.687	0.713	
	2	0.700		0.660	0.699			0.720	0.705	0.650							0.702	0.740	0.757	0.700	0.725	

*Data not used in statistical analysis.

APPENDIX W

BOCLE ROUND-ROBIN III INDIVIDUAL LABORATORY RESULTS

(1000 Gram Load)

		LABORATORIES																				
Fuel Sample	Ring No.	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U*
C.T. JP4	1	0.855	0.818	0.805	0.780	0.740	0.855	0.880	0.870	0.795	0.735	0.855	0.860	0.795	0.760	0.895	0.800	0.820	0.878	0.850	0.804	0.798
	2	0.870	0.782	0.835	0.815	0.785	0.935	0.870	0.860	0.815	0.690	0.740	0.840	0.795	0.735	0.890	0.768	0.840	0.806	0.837	0.909	0.798
ISOPAR M	1	0.880	0.914	0.910	0.853	0.730	0.785	0.870	0.880	0.865	0.815	0.850	0.905	0.830	0.850	0.910	0.866	0.890	0.903	0.900	0.853	0.858
	2	0.855	0.884	0.865	0.895	0.795	0.855	0.860	0.895	0.890	0.760	0.780	0.780	0.830	0.855	0.905	0.814	0.870	0.882	0.825	0.902	0.853
C.T. JET A	1	0.835	0.803	0.815	0.810	0.850	0.890	0.850	0.810	0.805	0.785	0.775	0.890	0.810	0.830	0.880	0.818	0.830	0.856	0.775	0.851	0.828
	2	0.830	0.808	0.810	0.833	0.830	0.915	0.860	0.815	0.820	0.745	0.750	0.790	0.795	0.835	0.845	0.795	0.860	0.799	0.775	0.853	0.850
JET A	1	0.565	0.589	0.565	0.582	0.525	0.530	0.570	0.585	0.575	0.545	0.575	0.565	0.550	0.540	0.590	0.550	0.588	0.573	0.562	0.569	0.550
	2	0.560	0.579	0.550	0.585	0.545	0.545	0.580	0.590	0.565	0.500	0.615	0.570	0.570	0.550	0.570	0.552	0.580	0.570	0.550	0.558	0.558
JP-7	1	0.885	0.919	0.895	0.935	0.905	0.895	0.950	0.875	0.900	0.845	0.845	0.920	0.900	0.895	0.920	0.942	0.910	0.932	0.800	0.891	0.838
	2	0.945	0.930	0.875	0.900	0.895	0.975	0.930	0.870	0.935	0.810	0.825	0.810	0.900	0.895	0.895	0.855	0.920	0.885	0.925	0.911	0.850
JP-4	1	0.570	0.599	0.570	0.557	0.540	0.550	0.590	0.590	0.570	0.555	0.490	0.580	0.570	0.555	0.560	0.536	0.570	0.564	0.550	0.573	0.545
	2	0.590	0.605	0.550	0.554	0.525	0.555	0.870	0.550	0.570	0.545	0.520	0.530	0.575	0.560	0.565	0.550	0.590	0.551	0.600	0.582	0.545
JP-5	1	0.580	0.599	0.590	0.598	0.575	0.570	0.580	0.605	0.595	0.560	0.565	0.605	0.590	0.575	0.615	0.588	0.610	0.623	0.600	0.591	0.545
	2	0.605	0.615	0.570	0.587	0.585	0.575	0.600	0.630	0.590	0.580	0.590	0.565	0.605	0.575	0.585	0.581	0.590	0.582	0.600	0.605	0.550
JET A-1, UK-1	1	0.700		0.660	0.677			0.700	0.700	0.665							0.647	0.683	0.715	0.675	0.687	
	2	0.685		0.668	0.660			0.700	0.680	0.675							0.647	0.675	0.681	0.675	0.693	
JET A-1, UK-2	1	0.785		0.740	0.749			0.770	0.745	0.750							0.789	0.803	0.856	0.800	0.798	
	2	0.790		0.750	0.738			0.770	0.770	0.745							0.796	0.810	0.851	0.787	0.814	

*Data not used in statistical analysis.

A P P E N D I X   X

DETAILS FOR DETERMINATION OF BOCLE TEST PRECISION

APPENDIX X

DETAILS FOR DETERMINATION OF BOCLE TEST PRECISION

SUMMARY OF RESULTS:

Note:
a) In the formulae below, X represents the sample mean.
b) Repeatability standard deviation is repeatability divided by 2*SQRT(2). Reproducibility standard deviation is reproducibility divided by 2*SQRT(2).

Data Set	Repeatability	Reproducibility
1) 500 gram Load		
All data	$.12471*X^{1.93}$	$.22687*X^{1.93}$
Excluding samples UK1 & UK2	$.13206*X^{1.96}$	$.23782*X^{1.96}$
Excluding labs B & F	$.11586*X^{1.86}$	$.21973*X^{1.86}$
Excluding samples UK1 & UK2, excluding labs B & F	$.12288*X^{1.89}$	$.23229*X^{1.89}$
Excl. all labs which did not test samples UK1 & UK2	$.10368*X^{1.86}$	$.17093*X^{1.86}$
2) 1000 gram Load		
All data	$.10946*X^{1.80}$	$.16673*X^{1.80}$
Excluding samples UK1 & UK2	$.11868*X^{1.87}$	$.17620*X^{1.87}$
Excluding labs B & F	$.10697*X^{1.72}$	$.15899*X^{1.72}$
Excluding samples UK1 & UK2, excluding labs B & F	$.11710*X^{1.80}$	$.16878*X^{1.80}$
Excl. all labs which did not test samples UK1 & UK2	$.092495*X^{1.84}$	$.11721*X^{1.84}$

ANALYSIS DESCRIPTIONS

Note:
a) Only 1% outliers were rejected
b) Transforms tested were square root, cube root, base 10 log, base 10 log (X+K), and power transform: X**P.
c) Analyzed with Exxon Research and Engineering Company-developed program "ASTM," which is based on ASTM RR D2-1007, with the exception that it follows ASTM E691-79 in using 2*SQRT(2) as the multiplier factor, rather than the Student's t value times SQRT(2) indicated in RR D2-1007 to convert the repeatability and reproducibility standard deviations to a repeatability and reproducibility value.

1) 500 gram Load

All data

a) Rejected Lab L, Sample CTA, Rep 1
b) Dependence of lab & rep standard deviations on sample mean seen, power transform P=-.8 applied.
c) Rejected Lab S, Sample JP4, Rep 1. Power transform seen to be still necessary after rejection and re-estimated to be P=-.93.

Excluding samples UK1 & UK2

a) Dependence of lab & rep standard deviations on sample mean seen, power transform P=-.88 applied.
b) Rejected Lab S, Sample JP4, Rep 1.
c) During re-estimation of power transform rejected Lab L, Sample CTA, Rep 1.
d) Power transform seen to be still necessary and estimated to be P=-.96.

Excluding labs B & F

a) Rejected Lab L, Sample CTA, Rep 1.
b) Dependence of lab & rep standard deviations on sample mean seen, power transform P=-.69 applied.
c) Rejected Lab S, Sample JP4, Rep 1.
d) Power transform still seen necessary and re-estimated to be P=-.86.

Excluding samples UK1 & UK2,
excluding labs B & F

a) Rejected Lab L, Sample CTA, Rep 1.
b) Dependence of lab & rep standard deviations on sample mean seen, power transform P=-.72 applied.
c) Rejected Lab S, Sample JP4, Rep 1.
d) Power transform still seen necessary and re-estimated to be P=-.89.

Excl all labs which did not
test samples UK1 & UK2

a) Rejected Lab S, Sample JP4, Rep 1.
b) Dependence of lab & rep standard deviations on sample mean seen, power transform P=-.86 applied.

2) 1000 gram Load

All data

a) Rejected Lab G, Sample JP4, Rep 2.
b) Dependence of lab & rep standard deviations on sample mean seen, power transform P=-.80 applied.

Excluding samples UK1 & UK2

a) Rejected Lab G, Sample JP4, Rep 2.
b) Dependence of lab & rep standard deviations on sample mean seen, power transform P=-.87 applied.

Excluding labs B & F

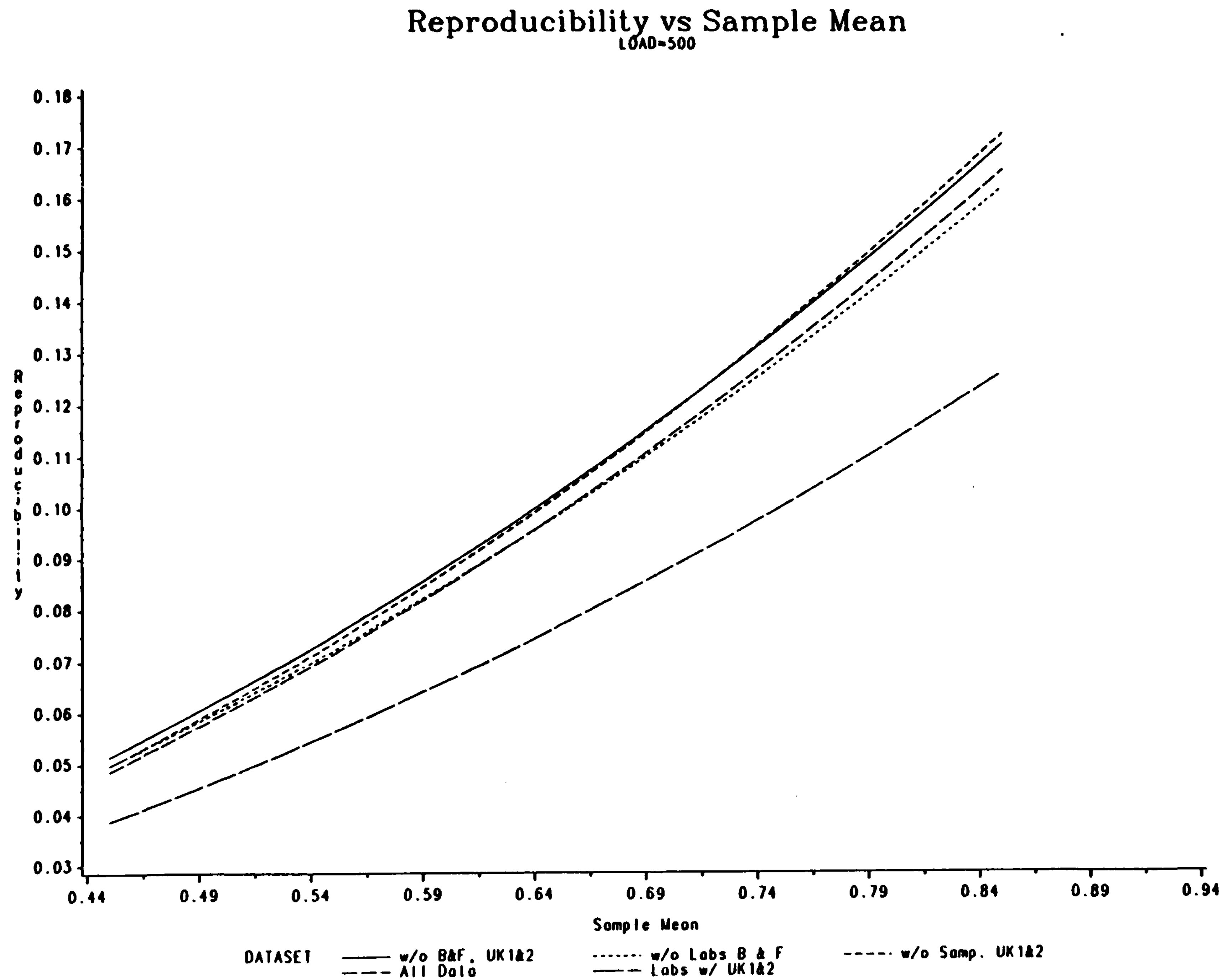
a) Rejected Lab G, Sample JP4, Rep 2.
b) Dependence of lab & rep standard deviations on sample mean seen, power transform P=-.72 applied.

Excluding samples UK1 & UK2,
excluding labs B & F

a) Rejected Lab G, Sample JP4, Rep 2.
b) Dependence of lab & rep standard deviations on sample mean seen, power transform P=-.80 applied.

Excl all labs which did not
test samples UK1 & UK2

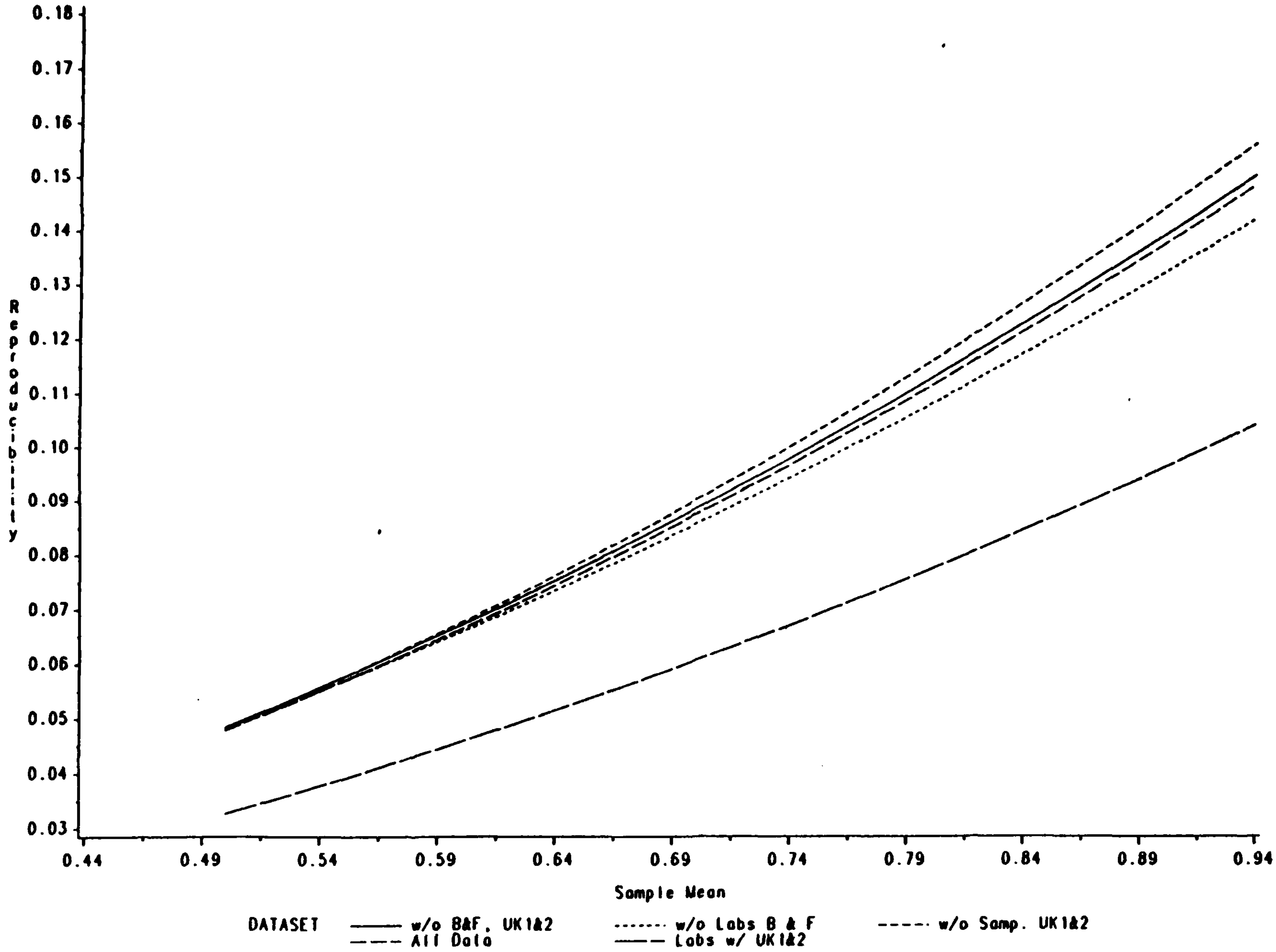
a) Rejected Lab G, Sample JP4, Rep 2.
b) Dependence of lab & rep standard deviations on sample mean seen, power transform P=-.96 applied.
c) Lab S, Sample JP7 rejected.
d) Power transform still seen necessary, re-estimated to be P=-.84.



Reproducibility vs Sample Mean
LOAD=500
Reproducibility
0.18
0.17
0.16
0.15
0.14
0.13
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.44
0.49
0.54
0.59
0.64
0.69
0.74
0.79
0.84
0.89
0.94
Sample Mean
DATASET
w/o B&F, UK1&2
All Data
w/o Labs B & F
Labs w/ UK1&2
w/o Samp. UK1&2

Reproducibility vs Sample Mean

LOAD=1000



Repeatability vs Sample Mean
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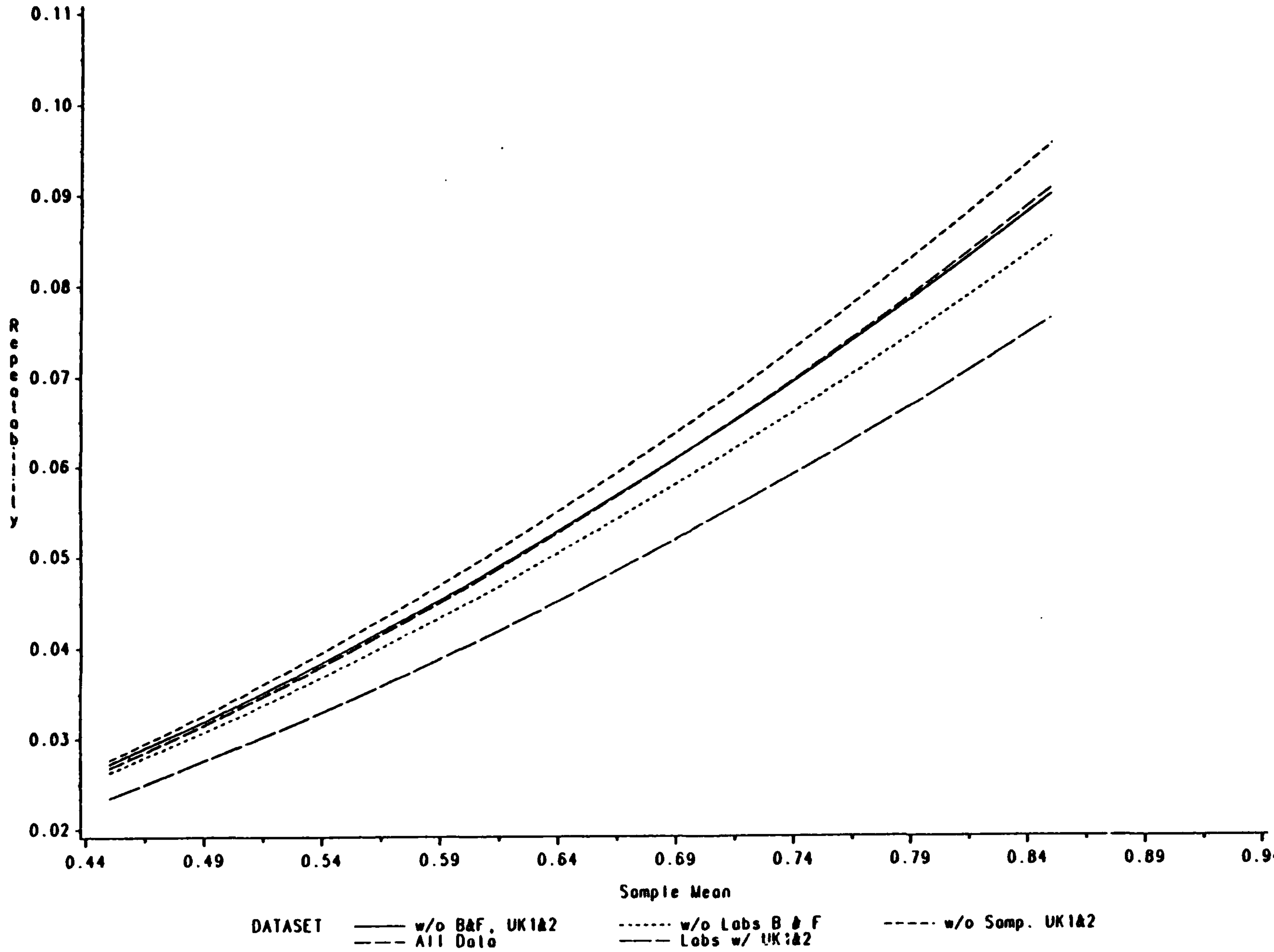

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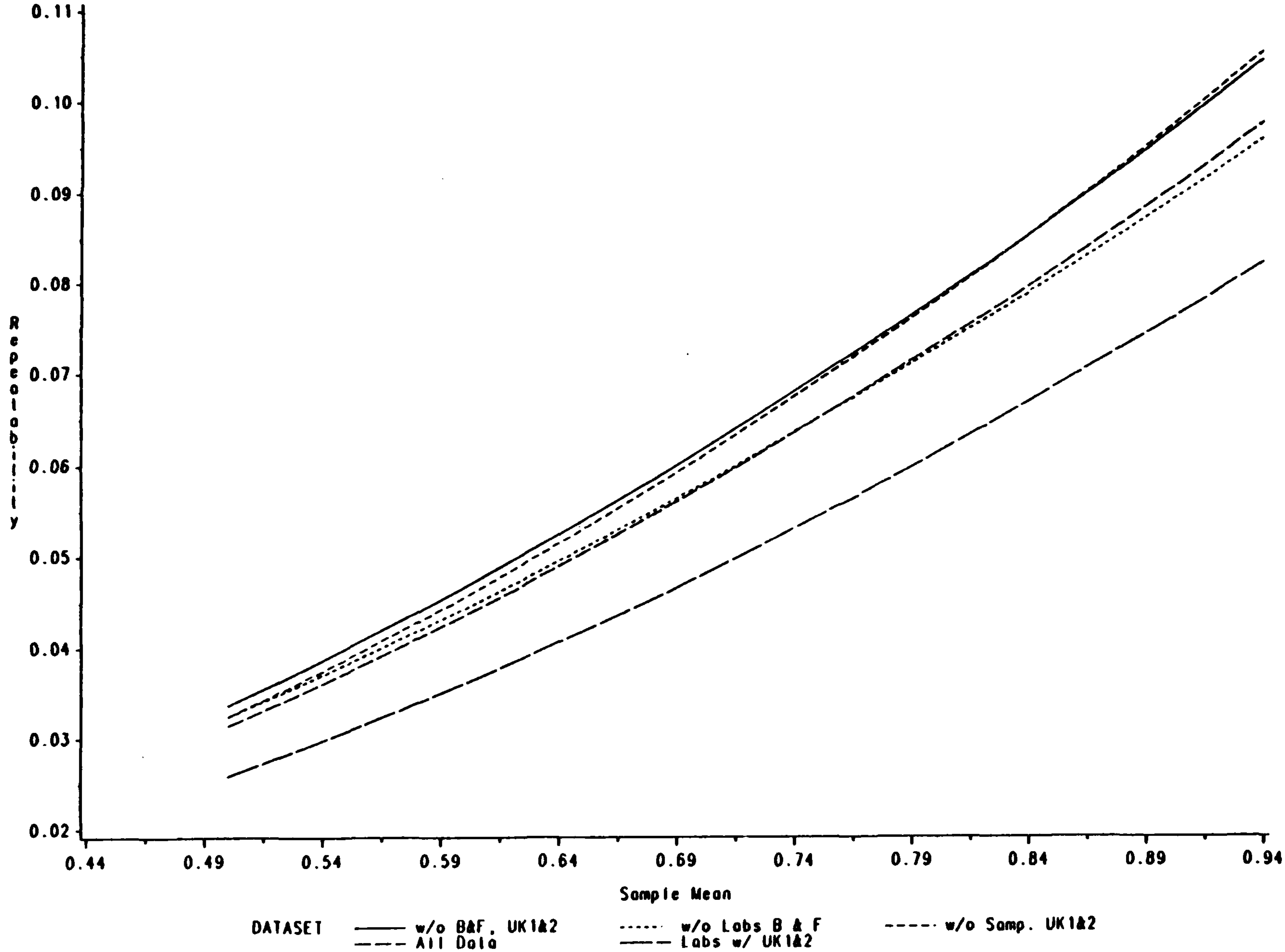

Reproducibility Standard Deviation vs Sample Mean

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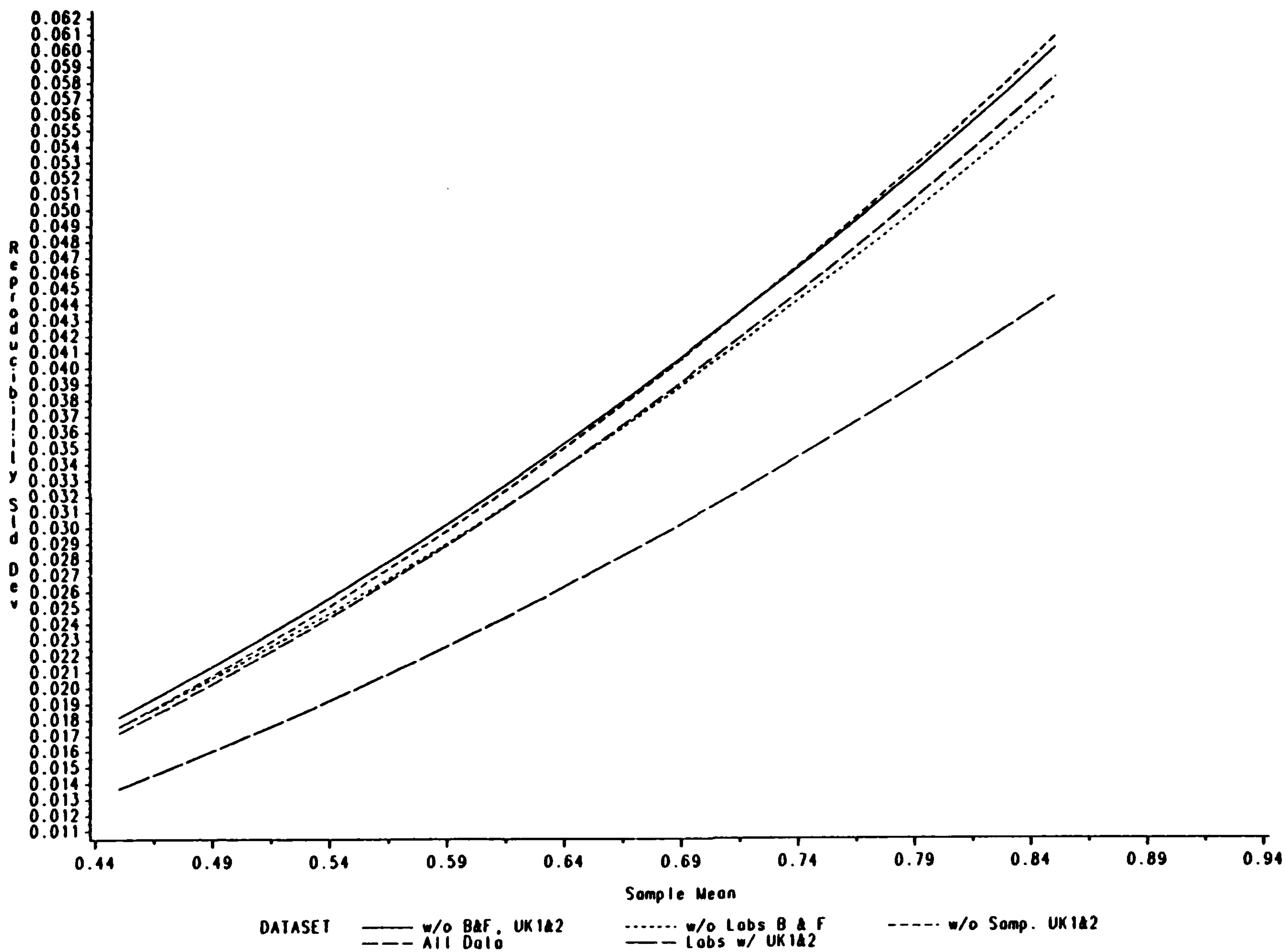

Reproducibility Standard Deviation vs Sample Mean

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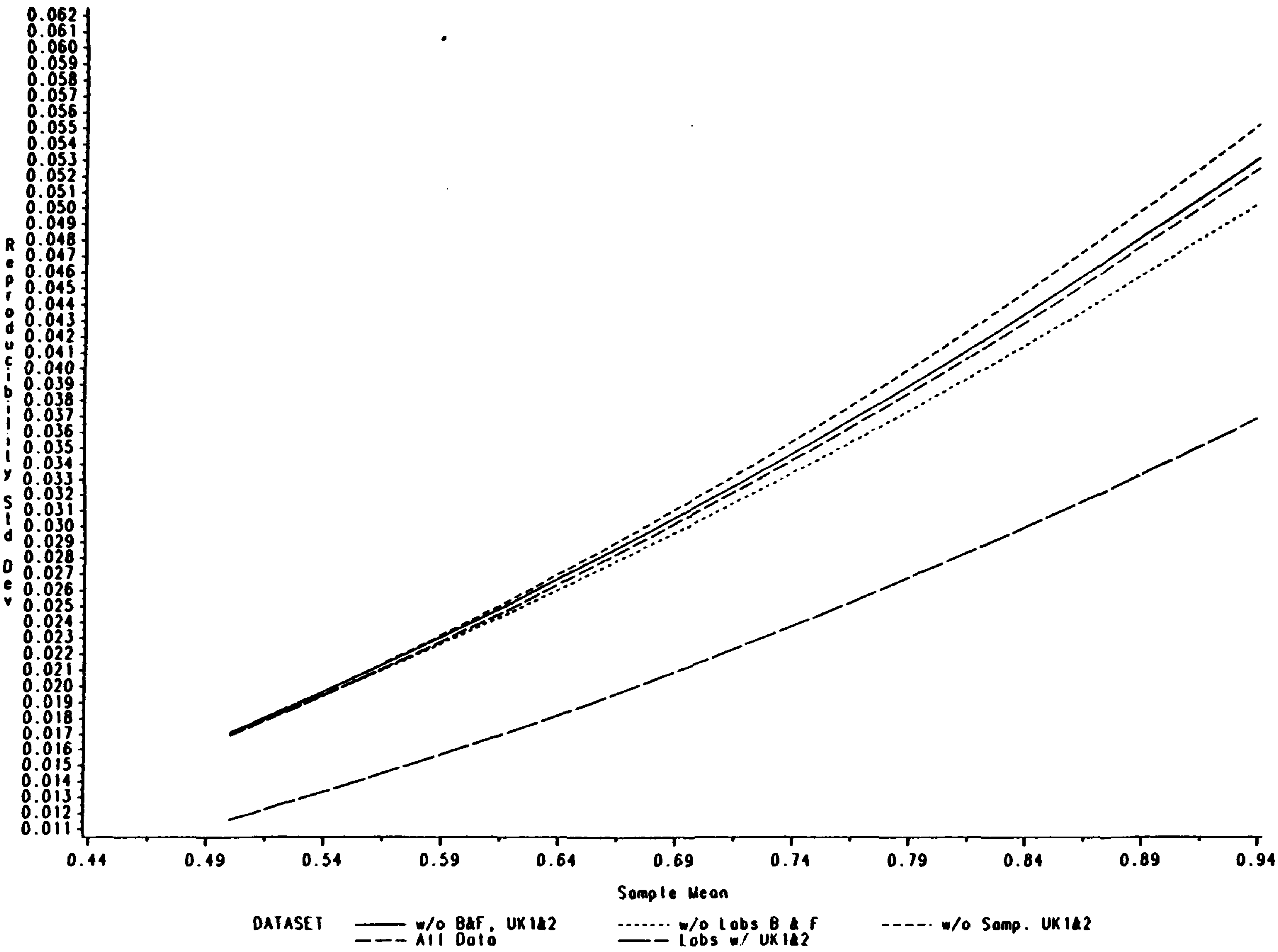

Repeatability Standard Deviation vs Sample Mean

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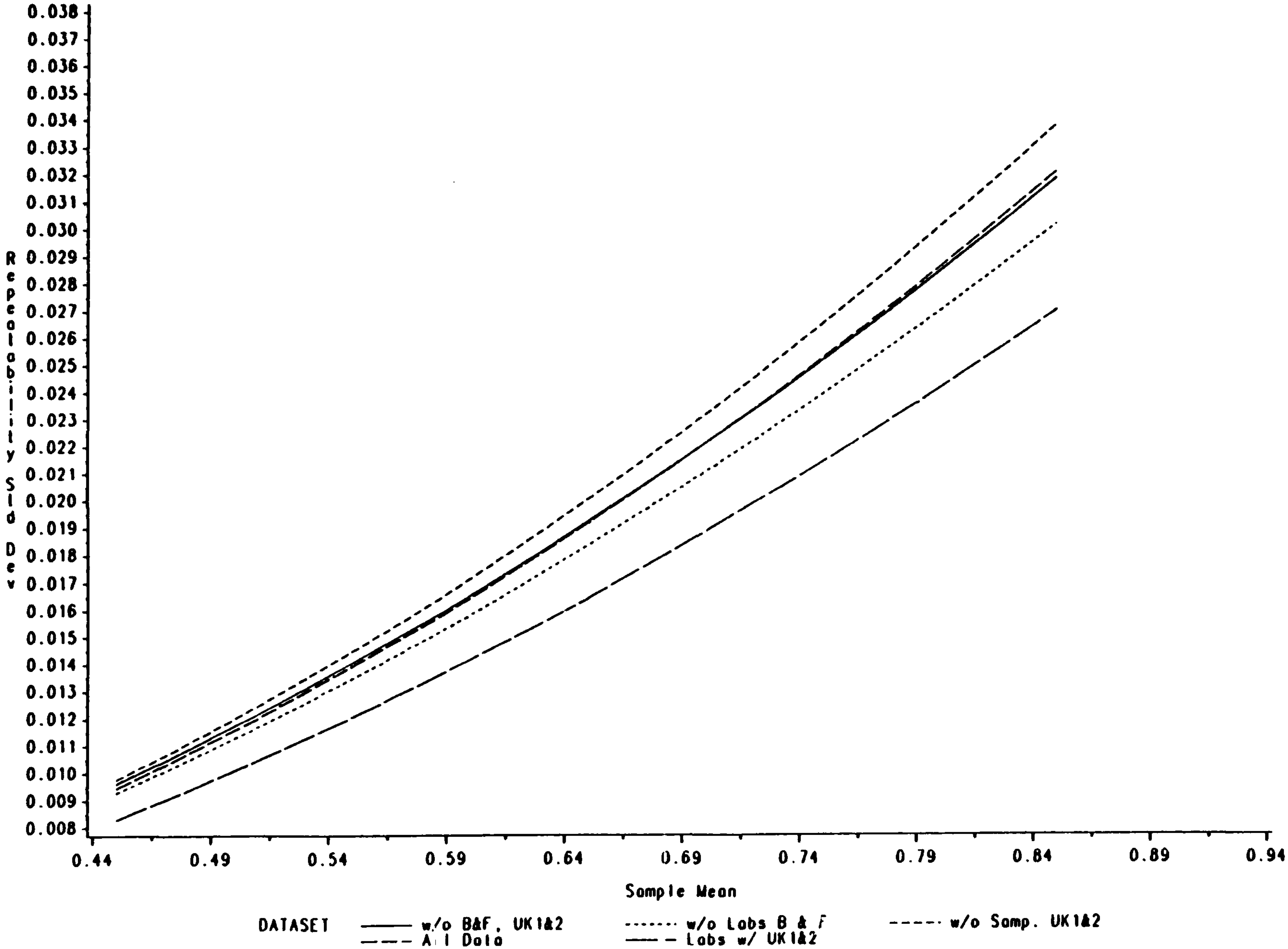
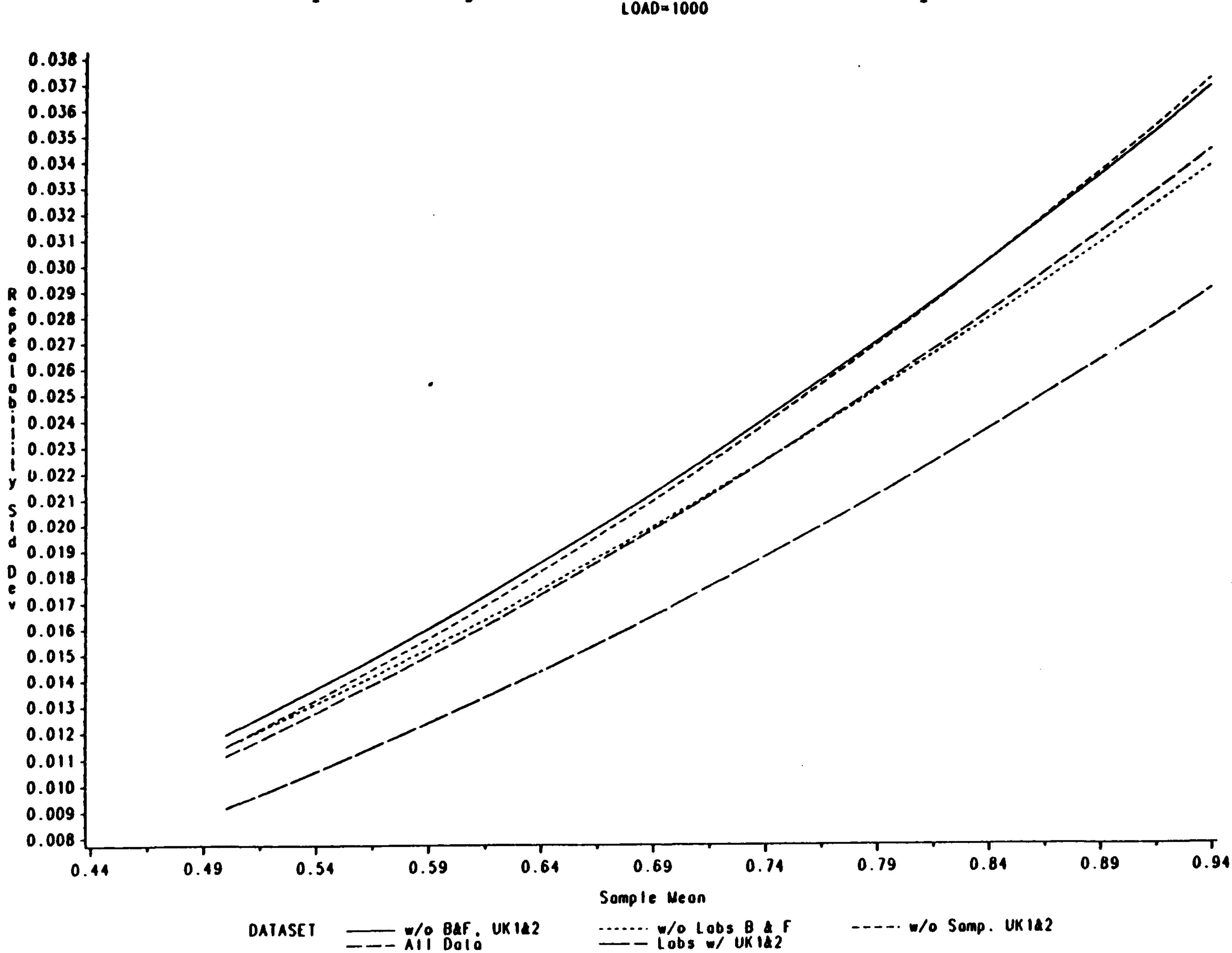


Repeatability Standard Deviation vs Sample Mean



APPENDIX Y

BOCLE ROUND-ROBIN III

STANDARD TEST METHOD FOR MEASUREMENT OF LUBRICITY OF LIQUID HYDROCARBON FUELS BY THE BALL-ON-CYLINDER LUBRICITY EVALUATOR

APPENDIX Y

STANDARD TEST METHOD FOR MEASUREMENT OF LUBRICITY OF LIQUID HYDROCARBON FUELS BY THE BALL-ON-CYLINDER LUBRICITY EVALUATOR[1] FOR THIRD ROUND-ROBIN

1.0 SCOPE

1.1 This method assesses the boundary lubrication properties of aviation fuels and similar hydrocarbon liquids on rubbing steel surfaces.

1.2 This standard may involve hazardous materials, operations and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this standard to consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use. For specific precautions, see 7.4, 7.8, 7.9, 7.10, 7.11.1, 7.11.2 and A1.

1.3 The values stated in SI units are to be regarded as the standard.

2.0 REFERENCED DOCUMENTS

2.1 ASTM Standards

D329, Specification for Acetone[3]
D770, Specification for Isopropyl Alcohol[3]
D1016, Purity of Hydrocarbons from Freezing Points[2]
D4306, Practice for Sampling Aviation Fuel for Tests Affected by Trace Contamination[4]
RR:D02-1007, Manual on Determining Precision Data[4]

2.2 Military Specification

MIL-I-25017, Inhibitor, Corrosion/Lubricity Improver, Fuel Soluble[5]

2.3 American Iron and Steel Institute Standard

AISI E-52100 Chromium Alloy Steel[6]

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(1) Current edition approved in 1988. Published 1988. This test method was developed by the Coordinating Research Council and is a part of their Report No. 560.
(2) Annual Book of ASTM Standards, Vol. 05.01
(3) Annual Book of ASTM Standards, Vol. 06.03
(4) Annual Book of ASTM Standards, Vol. 05.03
(5) Available from Naval Publications and Form Center, 5801 Tabor Avenue, Philadelphia, PA 19120.
(6) Available from American Iron and Steel Institute, 1000 16th Street, NW, Washington, D.C. 20036

2.4 American National Standards Institute Specification

ANSI B3.12, Metal Balls[7]

2.5 Society of Automotive Engineers

SAE 8720 Steel[8]

3.0 TERMINOLOGY

3.1 Description of Terms Specific to This Standard.

3.1.1 Lubricity - A property of the fluid, measured by the wear scar, in millimeters, produced on a stationary ball from contact with the fluid wetted rotating ring operating under closely controlled conditions.

3.1.2 Cylinder is defined as the ring and mandrel assembly.

4.0 SUMMARY OF METHOD

4.1 The fluid under test is placed in a test reservoir in which atmosphere air is maintained at 10% relative humidity. A non-rotating steel ball is held in a vertically mounted chuck and forced against an axially mounted steel ring with an applied load. The test ring is rotated at a fixed speed and receives a momentary exposure to the test fluid upon each revolution. The wear scar generated on the test ball is a measure of the fluid lubricating properties.

5.0 SIGNIFICANCE AND USE

5.1 Wear due to excessive friction resulting in shortened life of engine components such as fuel pumps and fuel controls have sometimes been ascribed to lack of lubricity in an aviation fuel.

5.2 The relationship of test results to aviation fuel system component distress due to wear has been demonstrated on occasions where boundary lubrication is a factor in the operation of the component.

5.3 The wear scar generated in the BOCLE test is sensitive to contamination of the fluids and test materials, the presence of oxygen and water in the atmosphere, and the temperature of the test.

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(7) Available from American National Standards Institute, 1430 Broadway, New York, NY 10018.

(8) Available from Society of Automotive Engineers, Inc., 400 Commonwealth Avenue, Warrendale, PA 15096.

6.0 APPARATUS

6.1 Ball-On-Cylinder Lubricity Evaluator (BOCLE), illustrated in Figures Y-1 and Y-2. The test requirements are listed in Table Y-I.[9]

6.2 Constant Temperature Bath-Circulator, capable of maintaining the fluid sample at 25$\pm$ 1.0C when circulating coolant through the base of the sample reservoir.

6.3 Microscope, capable of 100X magnification in graduations of 0.1 mm and incremented in divisions of 0.01 mm.[10]

6.3.1 Glass slide micrometer with a scale ruled in 0.01 mm divisions.[11]

6.4 Cleaning Bath, Ultrasonic seamless stainless steel tank with a capacity of 1.9 L (1/2 gal) and a cleaning power of 40W.[12]

7.0 REAGENTS AND MATERIALS

7.1 Test Ring, of SAE 8720 steel, having a Rockwell Hardness "C" Scale Number of 58 to 62 and a surface finish of 0.56 to 0.71 um (22 to 28 u in.) C.L.A. The dimensions are given in Figure Y-3.[13]

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(9) BOCLE units, BOC 100, made by InterAv, Inc., P.O. Box 792228, San Antonio, TX 78279 have been found satisfactory. Other units built to the drawings available from ASTM, 1916 Race Street, Philadelphia, PA 19103, meeting the test requirements of Table Y-I in accordance with the procedure of paragraph 3.2 of Guide-Lines for Equipment Supply, Listing and Replacement in ASTM D-2 Methods and Practices are considered acceptable. These units can have different operating procedures.

(10) The Unitron inverted metallurgical microscope monocular Model Series MEC or binocular Model Series BMEC from Unitron Instruments, Inc., 175 Express Street, Plainview, NY 11803, have been found satisfactory.

(11) Catalog No. 31-16-99 from Bausch and Lomb, Inc. has been found satisfactory. A certificate of traceability from the National Bureau of Standards is available.

(12) Ultrasonic cleaner with timer from Sonicor Instrument Corp., 1365 Marconi Boulevard, Copiaque, NY 11726 or VWR Scientific, P.O. Box 7900, San Francisco, CA 94120, have been found satisfactory.

(13) Test Rings, Part No. F25061 from FALEX CORP., 2055 Comprehensive Drive, Aurora, IL 60505, have been found satisfactory.

7.2 Mandrel, a 10° tapered short cylindrical section used for holding test ring.[14] See Figure Y-2.

7.3 Test Ball, RB 12.7 chrome alloy steel, made from AISI standard steel No. E-52100, with a diameter of 12.7 mm (0.5 in.) Grade 5 to 10 EP Finish. The balls are described in ANSI Specifications B3.12, for Metal Balls. The Extra-Polish finish is not described in that specification. The Rockwell C hardness shall be 64 to 66, a closer limit than is found in the ANSI requirement.[15]

7.4 Compressed Air (Warning - Compressed gas under high pressure. See Annex A1.1), containing less than 0.1 ppm hydrocarbons and 50 ppm water.

7.5 Desiccator, containing a non-indicating drying agent, capable to store test rings, balls, and hardware.

7.6 Gloves, clean, lint-free, cotton, disposable.

7.7 Wiper, wiping tissue, light duty, lint free, hydrocarbon free, disposable.[16]

7.8 Isooctane (Warning - Extremely flammable. Harmful if inhaled. Vapors may cause flash fire. See Annex A1.2), conforming to ASTM D1016, 95% purity minimum, 2,2,4 tri-methyl pentane.

7.9 Isopropyl Alcohol (Warning - flammable. See Annex A1.3), conforming to ASTM D770.

7.10 Acetone (Warning - Extremely flammable. Vapors may cause flash fire. See Annex A1.4), conforming to ASTM D329.

7.11 Reference Fluids[17]

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(14) Mandrel, Part No. M-0 from FALEX CORP., 2055 Comprehensive Drive, Aurora, IL 60505 or P/N BOC-2101 from InterAv, Inc. P.O. Box 792228,

(15) Test Balls, SKF Swedish, Part No. 310995A, RB 12.7, Grade 5 to 10 EP Finish, AISI 52100 Alloy from SKF Industries, Component Systems, 1690 East Race Street, Allentown, PA 90653 have been found satisfactory.

(16) Kimwipe wipers made be Kimberly-Clark Corp., Roswell, Georgia 30076 and Micro-Wipes #5310 made by Scott Paper Co., Philadelphia, PA have been found satisfactory.

(17) Reference Fluids, A & B available in Kit form as Part No. RF-930900 from Interav Inc., P.O. Box 792228, San Antonio, TX 78279.

7.11.1 Fluid A. A mixture to contain the specific 30 ppm by weight fuel soluble corrosion inhibitor/lubricity improver conforming to MIL-I-25017[18] (Warning - Flammable. See Annex A 1.5.) in Fluid B [19] (Warning - Flammable. See Annex A 1.5). Store in borosilicate glass with an aluminum foil lined insert cap. Store in dark area.

7.11.2 Fluid B. A narrow-cut isoparaffinic solvent.[19]

8.0 PREPARATION OF APPARATUS

8.1 Cleaning of Apparatus and Test Components

8.1.1 Test Rings, As Received

8.1.1.1 The test rings can be partially stripped of any wax-like protective coating by manually rubbing them with rags or paper towels saturated with isooctane.

8.1.1.2 Place partially cleaned rings in a clean 500 mL beaker. Transfer a sufficient volume of a 1 to 1 mixture of isooctane (Warning - See Annex A1.2) and isopropyl alcohol (Warning - See Annex A1.3) to the beaker such that the test rings are completely covered.)

8.1.1.3 Place beaker in ultrasonic cleaner and turn on for 15 minutes.

8.1.1.4 Remove test rings and repeat ultrasonic cleaning cycle of Section 8.1.1.3 with a clean beaker and fresh solvents.

NOTE 1: Handle all clean test rings with clean forceps or disposable gloves.

8.1.1.5 Remove test rings from beaker and rinse with isooctane. Dry. Rinse with acetone. (Warning - flammable. See Annex A1.4).

8.1.1.6 Dry and store in a desiccator.

8.1.2 Test Balls, As Received

8.1.2.1 Place balls in 300 mL beaker. Transfer a sufficient volume of a 1 to 1 mixture of isooctane and isopropyl alcohol to the beaker such that the test balls are completely covered by the cleaning solvent.

NOTE 2: Approximately a five-day supply can be processed at one time.

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(18) Additive shall be DCI-4A obtained from E.I. DuPont de Nemours and Company, 1007 Market Street, Wilmington, Delaware 19893.

(19) Solvent shall be ISOPAR M obtained from the Exxon Company, USA, P.O. Box 2180, Houston, TX 77001.

8.1.2.2 Place beaker in ultrasonic cleaner and turn on for 15 minutes.

8.1.2.3 Repeat the cleaning cycle of Section 8.1.2.2 with a clean beaker and fresh solvent.

8.1.2.4 Remove and rinse with isooctane. Dry. Rinse with acetone.

8.1.2.5 Dry and store in a desiccator.

8.1.3 Reservoir, Reservoir Cover, Ball Chuck, Ball Lock Ring

8.1.3.1 Rinse with isooctane.

8.1.3.2 Clean in an ultrasonic cleaner with a 1 to 1 mixture of isooctane and isopropyl alcohol for five minutes.

8.1.3.3 Remove and rinse with isooctane. Dry. Rinse with acetone.

8.1.3.4 Dry and store in a desiccator.

8.1.4 Hardware

8.1.4.1 The hardware and utensils, i.e. shaft, wrenches, tweezers, that come in contact with the test fluid shall be cleaned by washing thoroughly with isooctane and wiping with wiping tissue.

8.1.4.2 Store parts in desiccator when not in use.

8.1.5 After Test

8.1.5.1 Remove reservoir and cylinder.

8.1.5.2 Disassemble components and clean in an ultrasonic cleaner using a 1 to 1 mixture of isooctane and isopropyl alcohol for five minutes. Rinse with isooctane. Dry. Rinse with acetone. Reassemble components.

8.1.5.3 Dry and store in a desiccator.

NOTE 3: When testing the same fluid, it is permissible to clean the reservoir in-place. The reservoir is rinsed with isooctane. Wipe with disposable wiper to remove residual fuel related deposits and test debris. The reservoir is rinsed again with isooctane. Dry and final rinse with acetone. Dry. Care shall be taken to ensure that the fuel aeration tube is rinsed and dried during the cleaning procedure. Store parts in desiccator when not in use.

9.0 CALIBRATION AND STANDARDIZATION

9.1 Visually inspect test balls before each test. Discard balls that exhibit pits, corrosion or surface abnormalities.

9.2 Reference Fluids

9.2.1 Test each new batch of the reference fluids per Section 10 with a test ring qualified with the previous reference fluid.

9.2.2 Repeat for two additional tests.

9.2.3 Further tests are necessary if the wear scar diameters differ by more than 0.04 mm for Reference Fluid A and/or 0.08mm for Reference Fluid B.

9.2.4 Obtain the average wear scar diameter (WSD). The following are the typical reference fluid values for comparison with other test rings:

Reference Fluid A	0.57 mm average WSD
Reference Fluid B	0.85 mm average WSD

9.3 Test Ring Calibration

9.3.1 Test each new ring with Reference Fluid A.

9.3.1.1 Repeat test if the wear scar diameter does not agree within 0.04 mm WSD of the Reference Fluid A value in Section 9.2.4.

9.3.1.2 A third test shall be performed in the event the first two values obtained differ more than 0.04 mm from each other.

9.3.1.3 The ring shall be rejected when the results differ by more than 0.04 mm WSD from the Reference Fluid A value in Section 9.2.4.

9.3.2 Test each new ring with Reference Fluid B.

9.3.2.1 Repeat test if the wear scar diameter does not agree within 0.08 mm of the value in Section 9.2.4.

9.3.2.2 A third test shall be performed in the event the first two values obtained differ more than 0.08 mm of each other.

9.3.2.3 The ring shall be rejected when the results differ by more than 0.08 mm from the Reference Fluid B value in Section 9.2.4.

9.4 Leveling of Load Arm

NOTE 5: The level of the load arm shall be inspected prior to every test.

9.4.1 Level the motor platform by use of the circular bubble level and adjustable stainless steel legs.

9.4.2 Install a test ball in the retaining nut as described in Section 10.4.

9.4.3 Lower load arm by disengaging blue pull pin. Attach 500 g weight to end of load beam. Lower ball onto ring manually or by use of arm actuator switch.

9.4.4 Check level on top of load arm. The indicator bubble shall be centered in the middle of the two lines. If required, adjust the retaining nut screw to achieve a level load arm.

9.5 Assembly of Cylinder

9.5.1 Place a clean test ring on the mandrel and bolt the back plate to the mandrel as shown in Figure Y-2.

10.0 PROCEDURE

10.1 The summary of test conditions is included in Table Y-I.

10.2 Installation of Cleaned Test Cylinder

NOTE 6: The BOCLE is very sensitive to contamination problems. The greatest care shall be taken to adhere strictly to cleanliness requirements and to the specified cleaning procedures.

During handling and installation procedures, cleaned test parts (cylinder, balls, reservoir, and reservoir cover) shall be protected from contamination by wearing clean cotton gloves.

10.2.1 Rinse shaft with isooctane and wipe with disposable wiper.

10.2.2 Push the shaft through the left hand bearing and support bracket.

10.2.3 Hold the cylinder with the set screw hub facing left. Push the shaft through the cylinder bore, through the right hand bearing support bracket, and into the coupling as far as the shaft will go.

10.2.4 Align the coupling set screw with the flat keyway side of the cylinder shaft. Tighten set screw.

10.2.5 Set micrometer at 0.5 mm and slide cylinder to the left until it is firm against micrometer probe. Insure that cylinder set screw is directed toward the keyway (flat surface of shaft) and tighten set screw.

10.2.6 Back micrometer probe away from cylinder before drive motor is engaged.

10.3 Record on the Data Sheet (Figure Y-5) the ring number, if assigned, and the position of the test cylinder as indicated by the micrometer. The first and last wear tracks on a ring shall be approximately 1 mm in from either side.

10.3.1 For subsequent tests, reset cylinder to a new test position with the micrometer. The new position should be 0.75 mm from the last wear track on the ring and noted on the data sheet. After tightening the cylinder set screw to lock the cylinder in a new test position, the micrometer probe should be backed off, then advanced to the cylinder again. Check micrometer reading to ensure correct track spacing. Readjust position, if required. When the correct ring position is assured, back the micrometer probe away from the cylinder.

10.4 Install a clean test ball by first placing the ball in the retaining nut, followed by the blue retaining ring. Screw retaining nut onto the threaded chuck located on the load arm and hand tighten.

10.5 Secure the load beam in the Up position by insertion of the blue pin.

10.6 Install the clean reservoir. Install the blue spacing platform by raising the reservoir. Slide blue spacer platform into position under the reservoir. Place thermocouple in the hole provided at the rear left side of the reservoir.

10.7 Check load beam Level. Adjust, if necessary.

10.8 Transfer 50 mL ± 1 mL of the test fluid to the reservoir. Place cleaned reservoir cover in position and attach the 1/4" and 1/8" air lines to reservoir cover.

NOTE 7: Fluid shall be supplied in accordance with ASTM D4306.

10.9 Move power switch to On position.

10.10 Turn on compressed air cylinder. Adjust the delivery pressure to 207-345 kPa (30-50 psi) and the console air pressure approximately 100 kPa (14.5 psi).

10.11 Place arm lift actuator switch in the Up position.

10.12 Lower load beam by pulling blue pull pin. Hang 500 gram weight on end of load beam.

10.13 Start rotation of cylinder by switching motor drive to On. Set rotation to 240 ± 1 r/min.

10.14 Using the flow meters that control the wet and dry air flows, adjust conditioned air flow to read 3.8 L/min. Maintain 10.0 ± 0.2 percent relative humidity.

10.15 Adjust reservoir temperature as required until temperature stabilizes at 25 ± 1°C. Adjust thermostat of the heat exchanger circulating bath to obtain the required temperature.

10.16 Set fuel aeration timer for 15 minutes and adjust fuel aeration flowmeter to 0.5 L/min.

10.17 At completion of aeration, the whistle will sound and aeration will cease. Continue 3.8 L/min flow through the reservoir. Move arm lift actuator switch to Down position. In approximately 8 seconds the load arm will be lowered and the ball will gently make contact with the ring. Switch timer On for 30 minutes.

NOTE 8: The rate at which the load arm lowers is controlled by the arm lift actuator valve on the left side of the cabinet. This valve controls the bleed from the pneumatic arm lift actuator cylinder.

10.18 Check all test condition readouts and adjust as necessary. Record all necessary information on Data Sheet.

10.19 At the end of 30 minutes, the whistle will sound and the test load arm will automatically spring up. Turn timer to Off and move arm lift actuator switch to Up position.

10.20 Manually remove test weight. Lift test load arm up and secure with blue pull pin.

10.21 Remove reservoir cover and wipe revolving ring with a disposable wiper to remove residue from the test ring. Turn motor drive and power switch to Off.

10.22 Remove test ball from locking nut. Do not remove ball from blue retaining ring. Wipe ball clean with disposable wiper prior to microscopic examination.

11.0 MEASURE OF THE WEAR SCAR

11.1 Turn on microscope light and position test ball under microscope at 100X magnification.

11.2 Focus microscope and adjust stage such that wear scar is centered within the field of view.

11.3 Align the wear scar to a divisional point of reference on the numerical scale with the mechanical stage controls. Measure the major axis to the nearest 0.01 mm. Typical wear scars are illustrated in Figure Y-4. Record the readings on the data sheet.

11.4 Align the wear scar to a divisional point of reference on the numerical scale with the mechanical stage controls. Measure the minor axis to the nearest 0.01 mm. Record the readings on the data sheet.

11.5 Record condition of wear area if different from the reference standard test, i.e., debris color, unusual particles or wear pattern, visible galling, etc., and presence of particles in the reservoir.

12.0 CALCULATIONS

12.1 Calculate the wear scar diameter as follows:

$$WSD = (M + N)/2 \qquad (1)$$

where: WSD = wear scar diameter, mm
M = major axis, mm
N = minor axis, mm

13.0 REPORT

13.1 Report the wear scar diameter to the nearest 0.01 mm.

13.2 Report the description of the wear scar area.

13.3 Report deviations from the standard conditions of the test load, relative humidity and fuel temperature, etc.

14.0 PRECISION AND BIAS

14.1 Precision[20] - The precision was developed for fuels with a wear scar diameter between 0.45 and 0.95mm. The precision of the method determined by the statistical examination of interlaboratory test results[21] is as follows:

14.1.1 Repeatability - The difference between two test results obtained by the same operator with the same apparatus under constant operating conditions on identical test material would, in the long run, in the normal and correct operation of the test method, exceed the following values in only one case in twenty.

$$\text{Repeatability} = 0.109\,(WSD)^{1.80} \qquad (2)$$

14.1.2 Reproducibility - The difference between two single and independent results obtained by different operators working in different laboratories on identical test material would, in the long run, exceed the following values only in one case in twenty.

$$\text{Reproducibility} = 0.167\,(WSD)^{1.80} \qquad (3)$$

14.2 Bias - The procedure in Test Method DXXXX for Measurement of Lubricity of Liquid Hydrocarbon Fuels by the Ball-On-Cylinder Lubricity Evaluator has no bias because the value of lubricity can be defined only in terms of a test method.

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(20) The precision statement was determined using the materials listed in Footnotes 13, 14, and 15.

(21) The details used for determining the test precision may be obtained from ASTM, 1916 Race Street, Philadelphia, PA 19103, by requesting RR:DD02-XXXX.

TABLE Y-I

STANDARD OPERATING CONDITIONS

Fluid Volume	50 ± 1.0 mL
Fluid Temperature	25 ± 1°C
Conditioned Air	10 ± 0.2% relative humidity at 25 ± 1°C

Fluid Pretreatment 0.50 L/min flowing through and 3.3 L/min over the fluid for 15 minutes.

Fluid Test Conditions 3.8 L/min flowing over the fluid.

Applied Load	1000g (500g weight)
Cylinder Rotational Speed	240 ± 1 r/min
Test Duration	30 ± 0.1 minutes

FIGURE Y-1

BALL-ON-CYLINDER LUBRICITY EVALUATOR

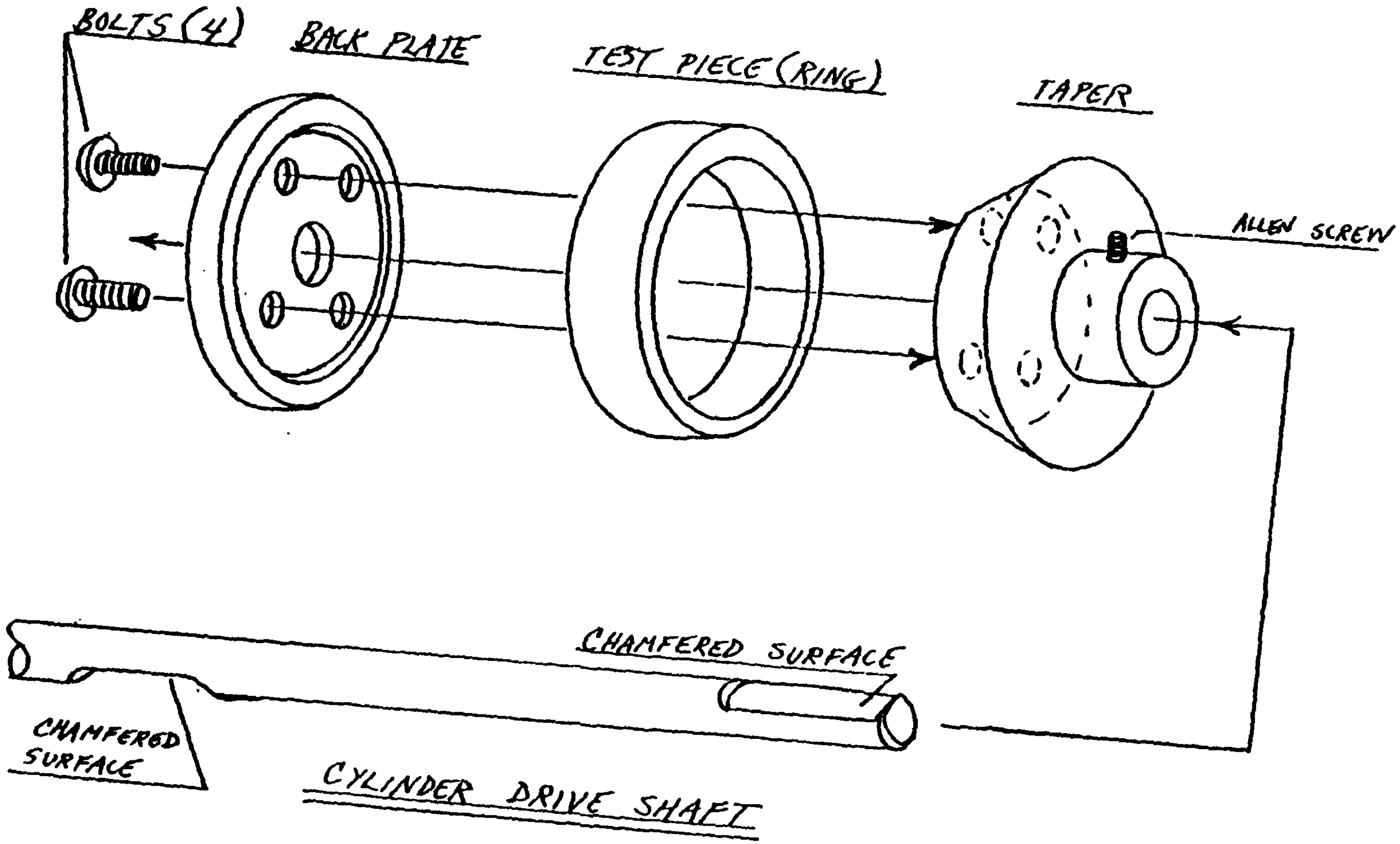
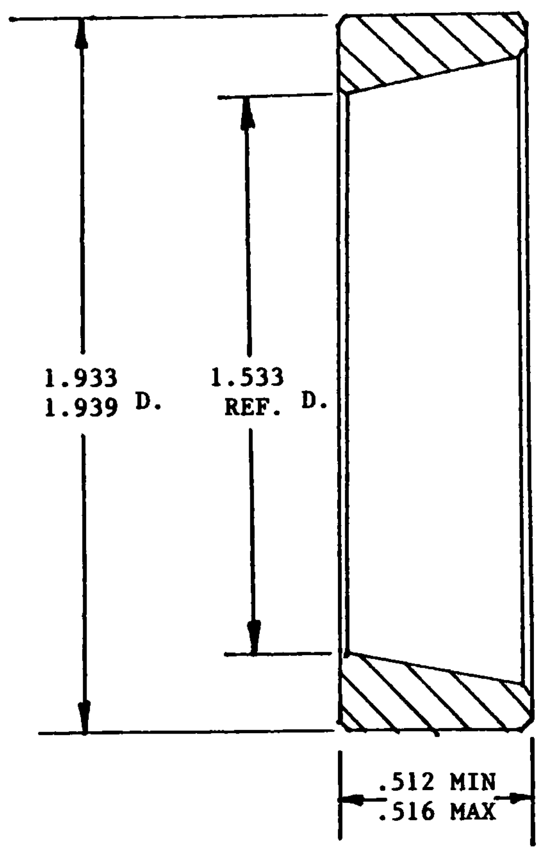


FIGURE Y-2

RING MANDREL ASSEMBLY



METRIC EQUIVALENT

in.	mm
0.512	13.00
0.516	13.11
1.533	38.94
1.933	49.10
1.939	49.25

MATERIAL: STEEL #8720 MODIFIED
HEAT TREAT: 58 - 60 Rc
FINISH: 20 - 30 RMS
DIMENSIONS: INCHES

FIGURE Y-3

BOCLE TEST RING

FIGURE Y-4

TYPICAL BOCLE WEAR SCARS

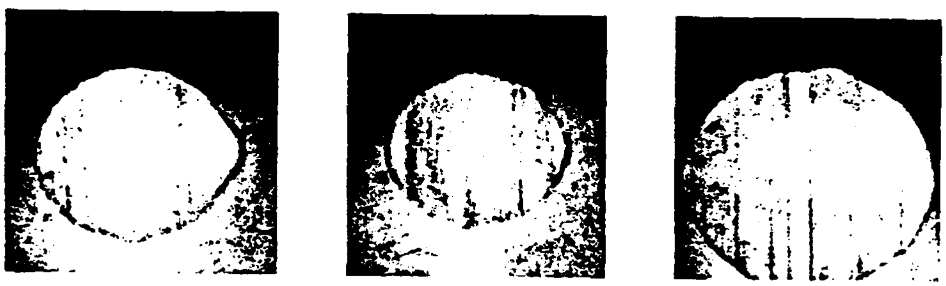


FIGURE Y-5

DATA SHEET

Ball-On-Cylinder Lubricity Evaluator Date______________

Sample:

Ring No.________________Track No.____________________Ball No.______________

Ambient Temperature, C ______________
Base Temperature, C Start ______________
Base Temperature, C End ______________
Base Temperature Controlled (Y/N) ______________

Precondition Reservoir, Time ______________
Start Test, Time ______________
Test Air Humidity ______10______
Ring Speed, RPM ______240______
Applied Load, Grams ______1000______
Volume Fuel Used, Ml ______________

Type Scar: Elliptical Circular Other

Minor Axis, mm ________
Major Axis, mm ________
WSD, mm ________

Observations:____
____
____

ANNEX

(Mandatory Information)

A1. PRECAUTIONARY STATEMENTS

A1.1 COMPRESSED AIR (CYLINDER)

WARNING - Compressed gas under high pressure. Use with extreme caution in the presence of combustible material, since the autoignition temperatures of most organic compounds in air are drastically reduced at eleveated pressures.

Keep cylinder valve closed when not in use.

Always use a pressure regulator. Release regulator tension before opening cylinder.

Do not transfer to cylinder other than one in which air is received. Do not mix gases in cylinder.

Do not drop cylinder. Make sure cylinder is supported at all times.

Stand away from cylinder outlet when opening cylinder valve.

Keep cylinder out of sun and away from heat.

Keep cylinders from corrosive environment.

Do not use cylinder without label.

Do not use dented or damaged cylinders.

For technical use only. Do not use for inhalation purposes.

A1.2 ISOOCTANE

WARNING - Extremely flammable. Harmful if inhaled. Vapors may cause flash fire.

Keep away from heat, sparks, and open flames.

Keep container closed.

Use with adequate ventilation.

Avoid build-up of vapors and eliminate all sources of ignition, especially nonexplosion-proof electrical apparatus and heaters.

Avoid prolonged breathing of vapor or spray mist.

Avoid prolonged or repeated skin contact.

A1.3 ISOPROPYL ALCOHOL

WARNING - Flammable.

Keep away from heat, sparks, and open flame.

Keep container closed.

Use with adequate ventilation.

Avoid prolonged breathing of vapor or spray mist.

Avoid contact with eyes and skin.

Do not take internally.

A1.4 ACETONE

WARNING - Extremely flammable. Vapors may cause flash fire.

Keep away from heat, sparks, and open flame.

Keep container closed.

Use with adequate ventilation.

Avoid build-up of vapors, and eliminate all sources of ignition, especially nonexplosion-proof electrical apparatus and heaters.

Avoid prolonged breathing of vapor of spray mist.

Avoid contact with eyes or skin.

A1.5 ISOPARAFFINIC SOLVENT AND FUEL ADDITIVE

WARNING - Flammable. Vapor harmful.

Keep away from heat, sparks, and open flame.

Keep container closed.

Use with adequate ventilation.

Avoid breathing vapor or spray mist.

Avoid prolonged or repeated contact with skin.